Physics of the Heavy Flavor Tracker at STAR

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1) Au+Au collisions

- measure heavy-quark hadron v_2, the heavy-quark collectivity to study light-quark thermalization
- measure di-leptions to study the direction radiation from the hot/dens medium
- measure heavy-quark energy loss to study pQCD in hot/dense medium

2) p+p collisions

- measure energy dependence of the heavy-quark production
- measure CP with W production at 500 GeV
- measure gluon structure with heavy quarks and direct photons

Outline

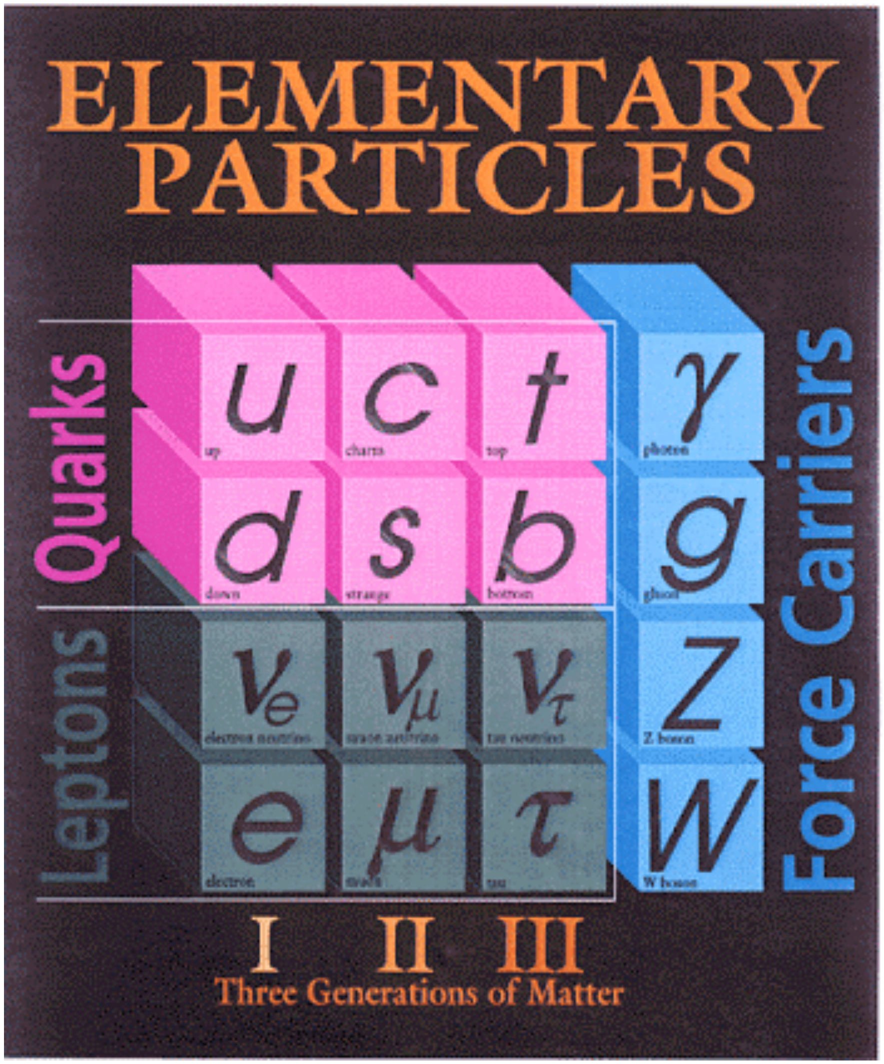
1) Introduction

2) Recent results from RHIC
  - Jet quenching
  - Partonic collectivity

3) New frontier - heavy quark production
  - HQ collectivity: test light quark thermalization
  - HQ energy loss: test pQCD in hot/dense medium

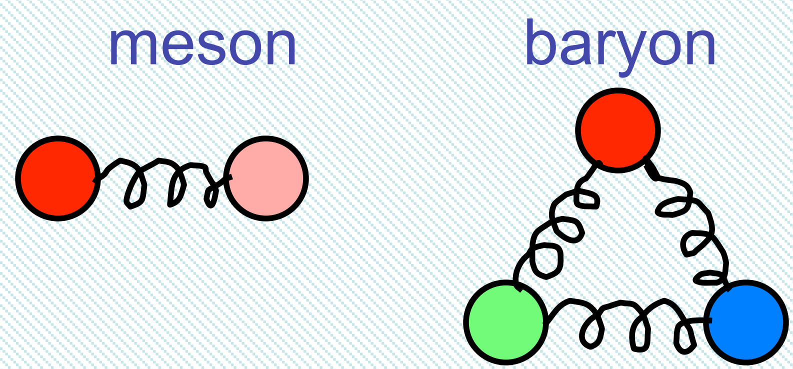
4) Proton helicity structure at RHIC

Quantum Chromodynamics



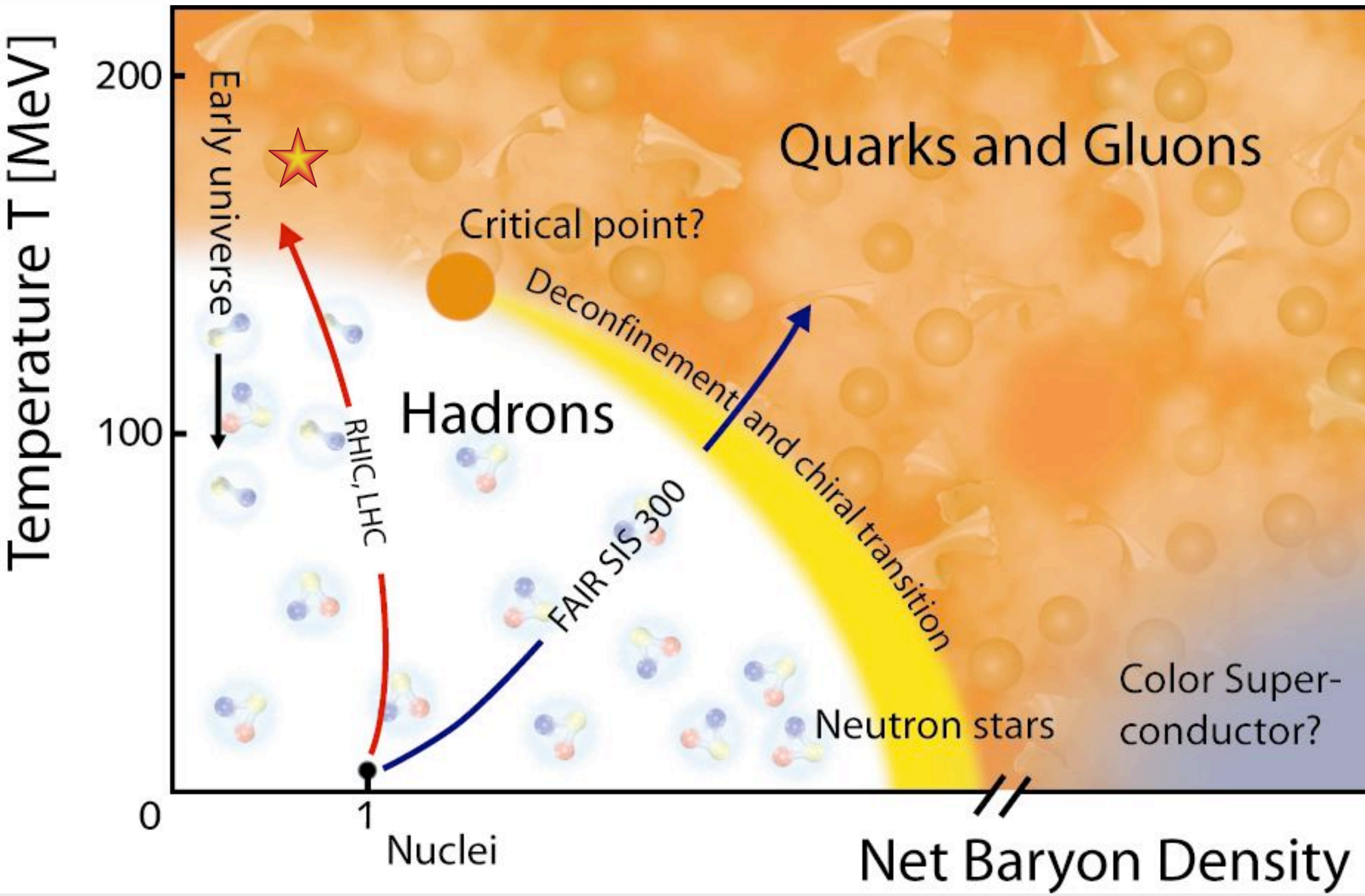
1) Quantum Chromodynamics (QCD) is the established theory of strongly interacting matter.

2) Gluons hold quarks together to from hadrons:



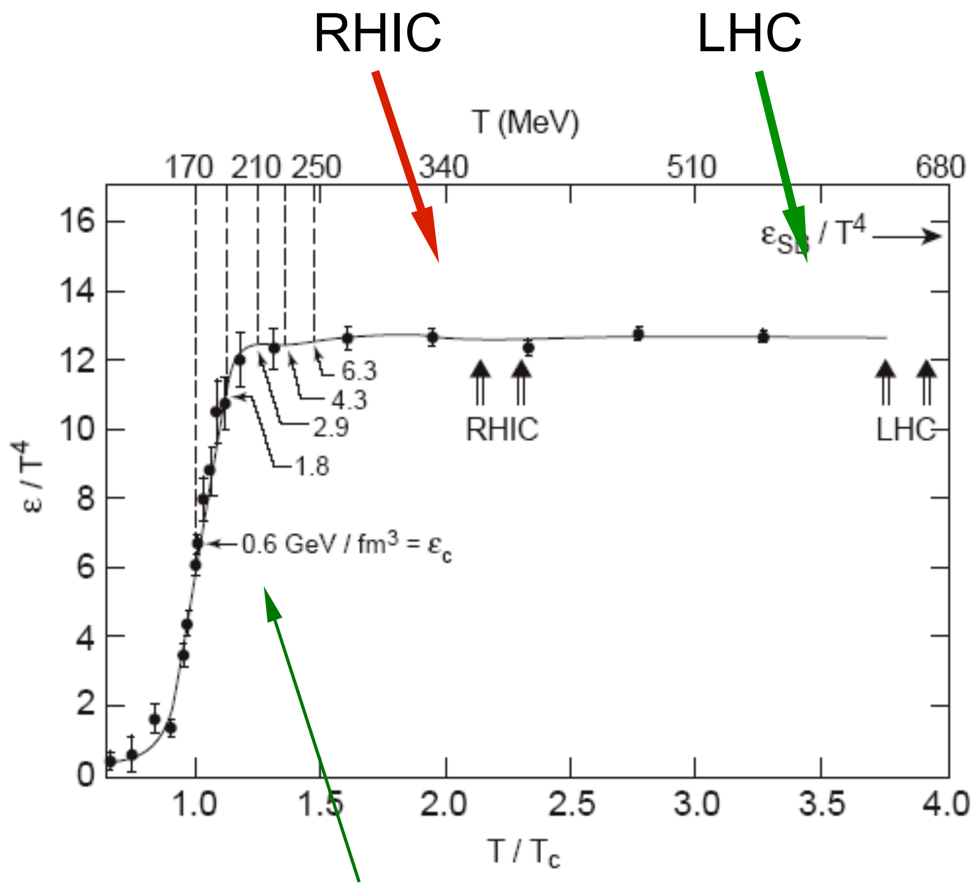
3) Gluons and quarks, or partons, typically exist in a color singlet state: ***confinement***.

The QCD Phase Diagram



Take from P. Senger

QCD on Lattice



Lattice calculations predict

$T_c \sim 160 \pm 20$ MeV

1) Large increase in ε,
   a fast cross cover !

2) Does not reach ideal,
   non-interaction S. Boltzmann
   limit !

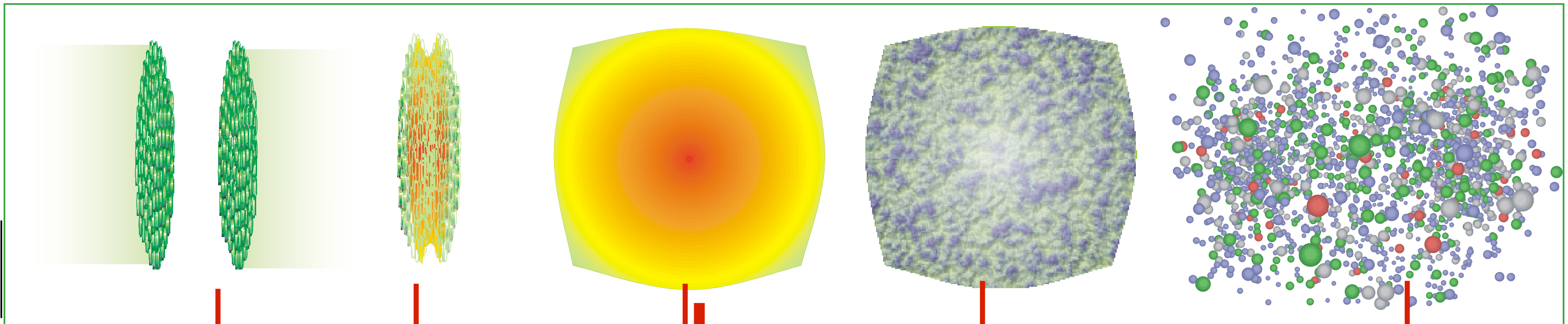
⇒ many body interactions

⇒ Collective modes

⇒ Quasi-particles are necessary

Y. Aoki, Z. Fodor, S.D. Katz, K.K. Szabo, PLB643 46(06); hep-lat/0609068
*Z. Fodor et al, **JHEP** 0203:014(02)*
Z. Fodor et al, hep-lat/0204029
*C.R. Allton et al, PR**D66**, 074507(02)*
F. Karsch, Nucl. Phys. A698, 199c(02).

High-energy Nuclear Collisions



S. Bass

Initial conditions

Initial high Q^2 interactions

Parton matter - QGP - The hot-QCD

Hadronization and Freeze-out

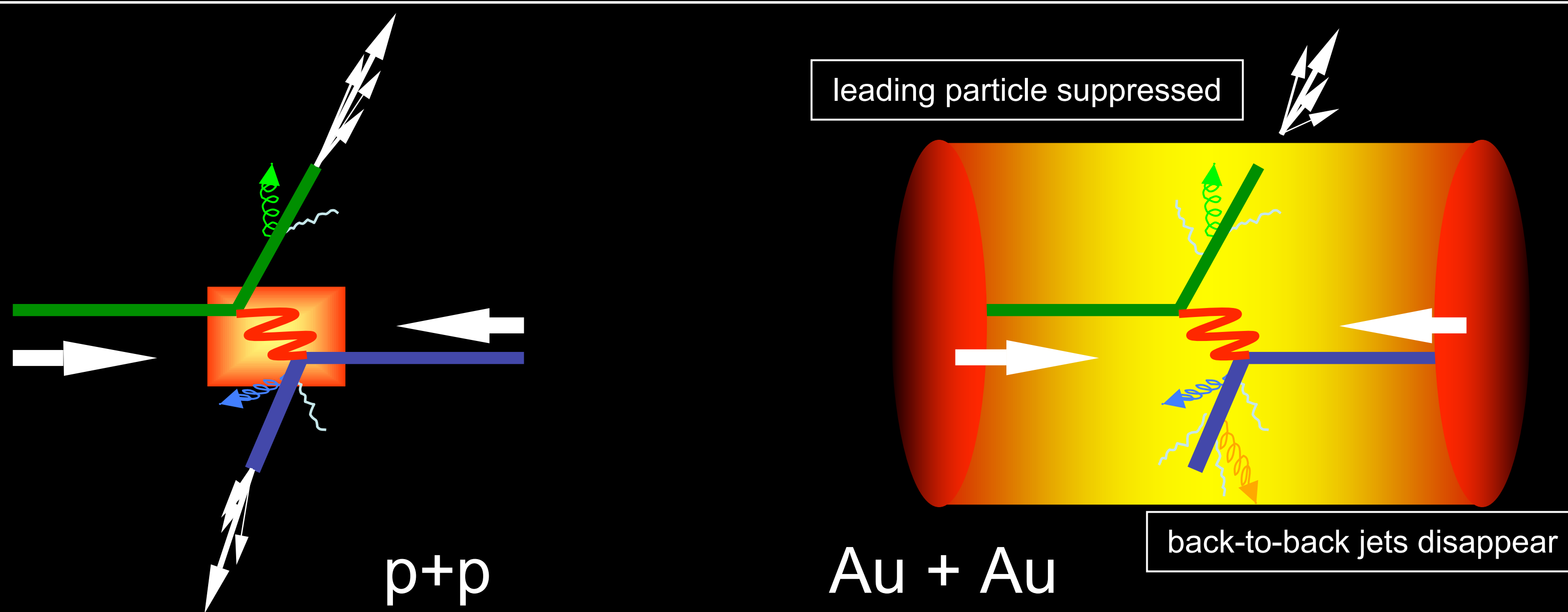
Experime... ac...

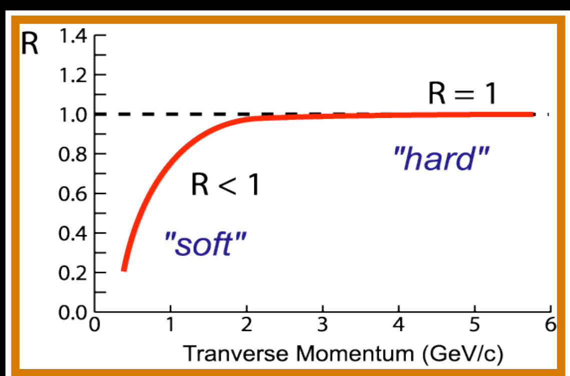
(1) Hard scattering production - QCD prediction
(2) Interactions with medium - deconfinement/thermalization
(3) Initial parton density

- **Energy**
- **Collect**
- Charm - productions plus the combination (1) and (2)

(1) Initial condition in high-energy nuclear collisions
(2) Cold-QCD-matter, small-x, high-parton density
- parton structures in nucleon / nucleus

Energy Loss in A+A Collisions

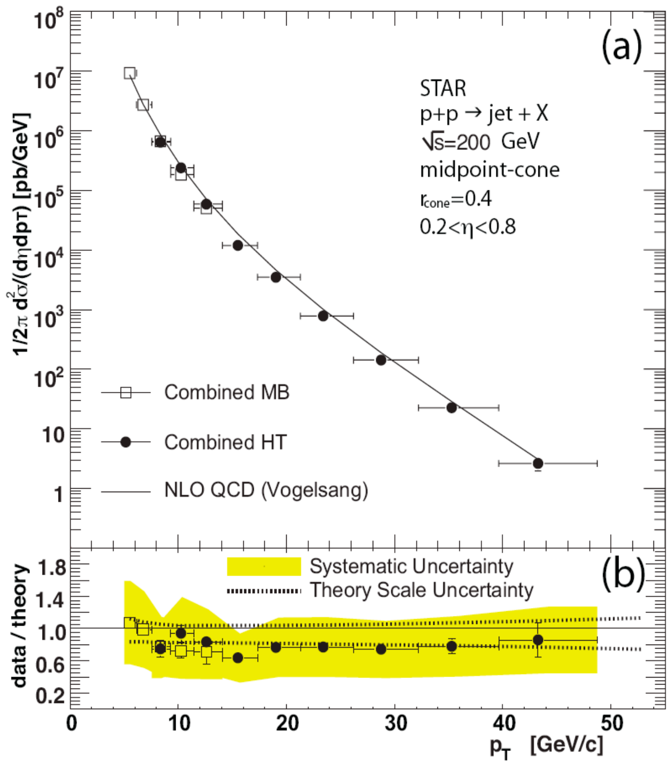


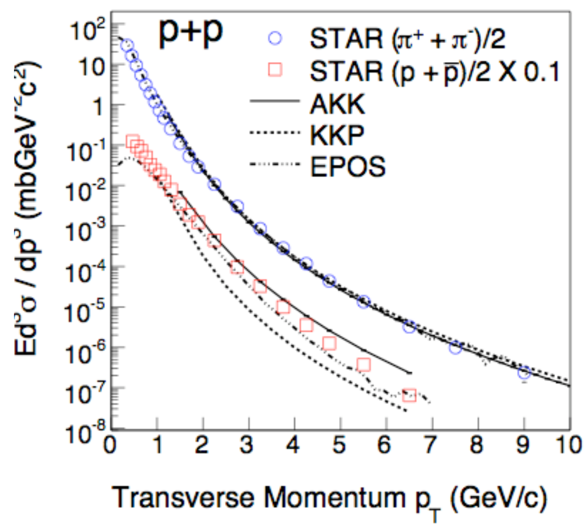


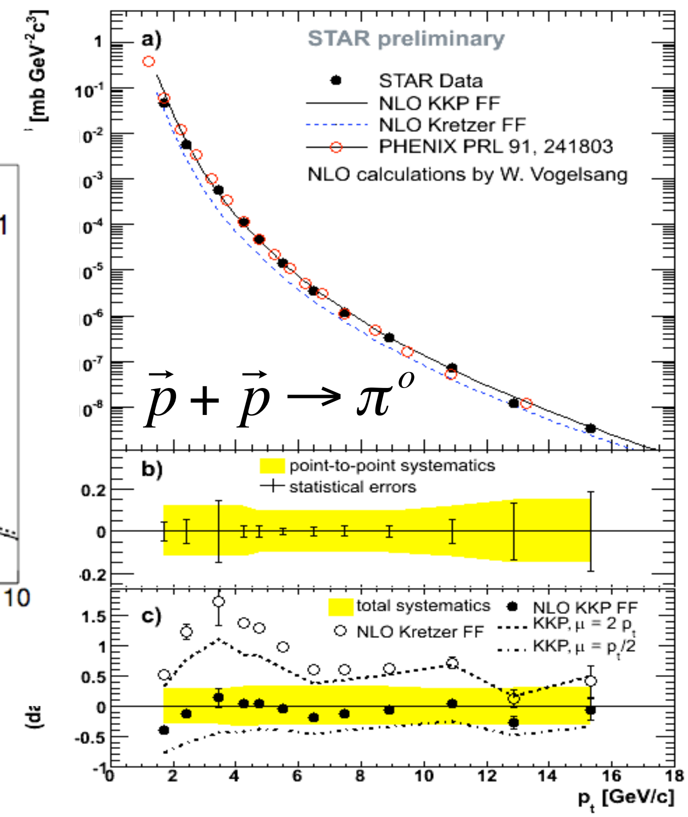
Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2N^{AA} / dp_T d\eta}{d^2\sigma^{NN} / dp_T d\eta}$$

Inclusive cross-section (jets, $\pi^{0,\pm}$,$p^{\pm}$)





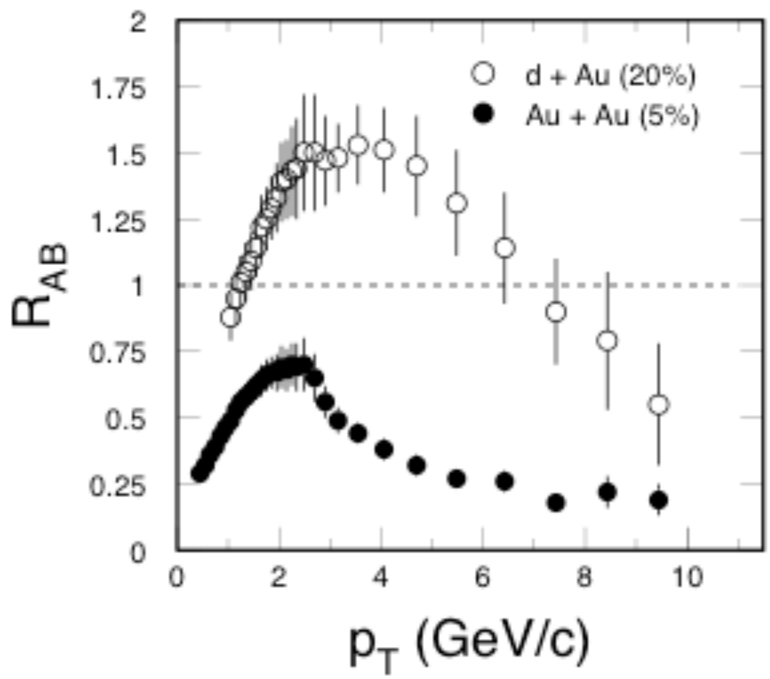


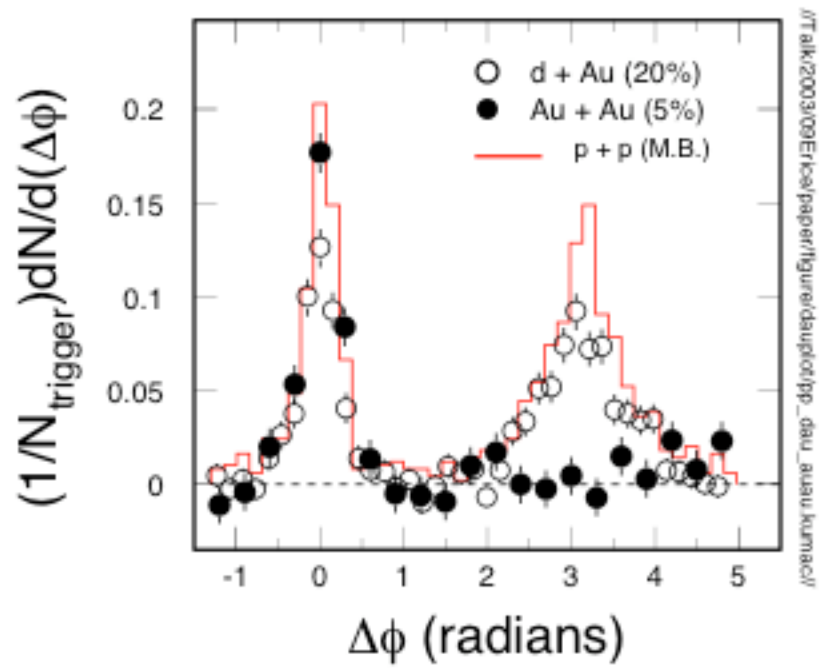
Mid-y jets, $\pi^{0,\pm}$ and $p^{\pm}$ productions are well reproduced by NLO pQCD calculations over many orders of magnitude ⇒

1) powerful tool for analyzing spin physics.
2) reliable reference for study high-energy nuclear collisions.

*STAR: PRL **97**, 252001(06); PL **B637**, 161(06)*

Suppression and Correlation





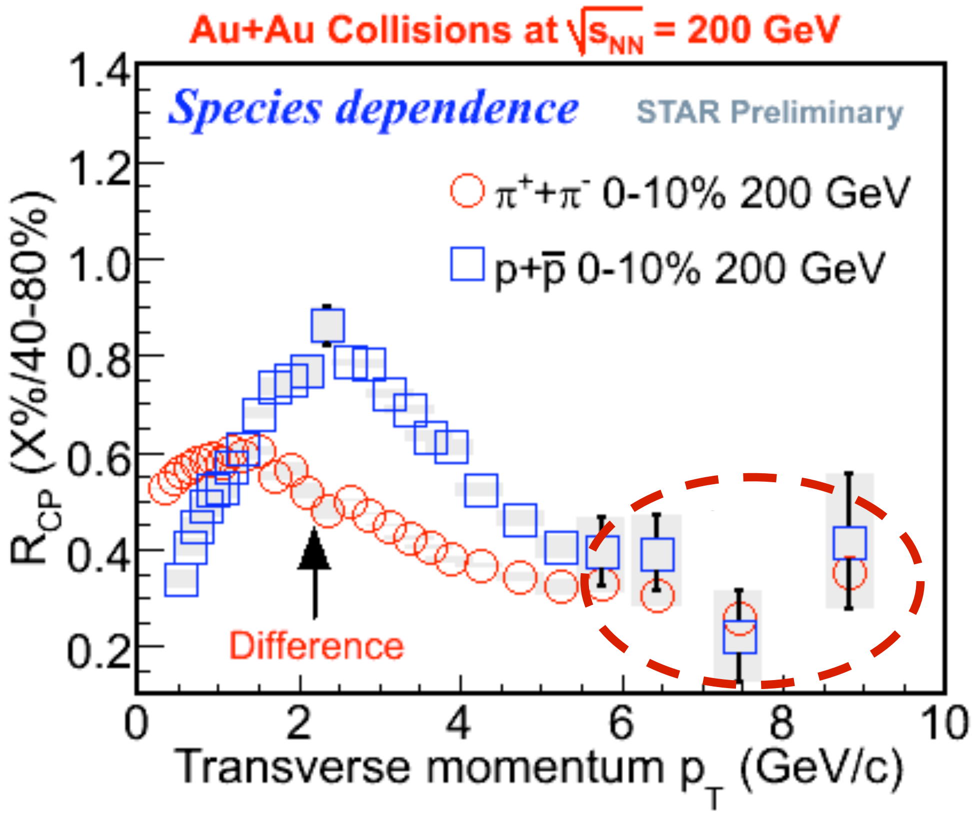
In central Au+Au collisions: hadrons are suppressed and back-to-back 'jets' are disappeared. Different from p+p and d+Au collisions.

Energy density at RHIC: $\boldsymbol{\varepsilon}$ > 5 GeV/fm^3 ~ 30$\boldsymbol{\varepsilon_0}$

Parton energy loss:	Bjorken	1982
("**Jet quenching**")	Gyulassy & Wang	1992

…

A pQCD Study



- At RHIC energy, baryons are mostly from gluons and pions are mostly from quark jets.

- Observation at high p_T :

$R_{CP}(\pi) \sim R_{CP}(p)$

$R_{CP}(K) \sim R_{CP}(\Lambda)$

- pQCD color factor effects:

$\Delta E(g)/\Delta E(q) \sim 9/4$

⇨ ***A clear challenge to pQCD predictions!***

⇨ ***Future tests with charm hadrons(quarks) and ϕ-meson(gluon).***

STAR: *nucl-ex/0703040. Phys. Lett. B, in print*

Lesson Learned - QCD at Work

(1) Spectra at intermediate p_T show evidence of suppression up to $p_T \sim 10$ GeV/c;

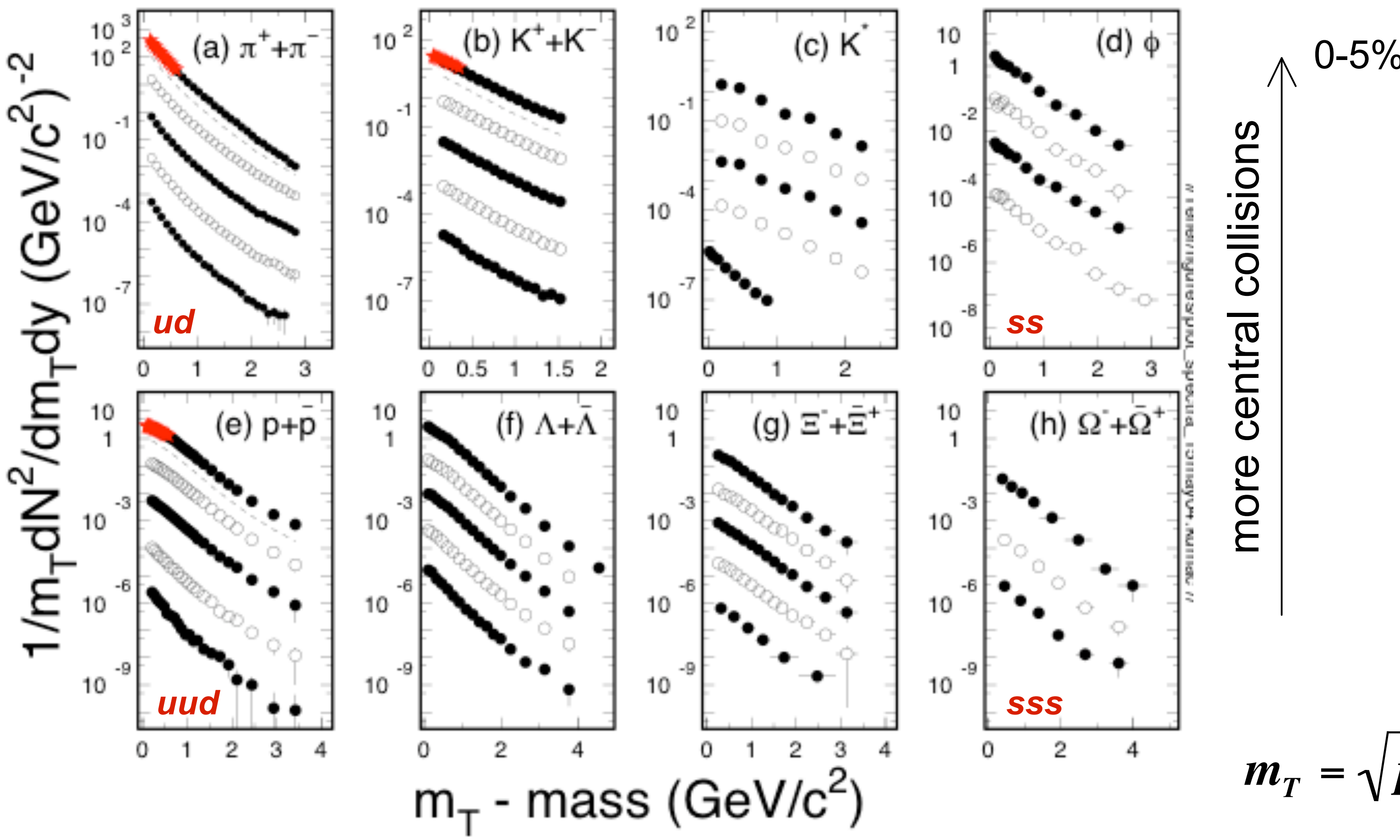
(2) Jet-like behavior observed in correlations:
- hard scatterings in AA collisions
- disappearance of back-to-back correlations;

(3) Effect of color factors not yet observed

⇨ ***Energy loss processes should lead to progressive equilibrium in the medium***

Hadron Spectra from RHIC

p+p and Au+Au collisions at 200 GeV



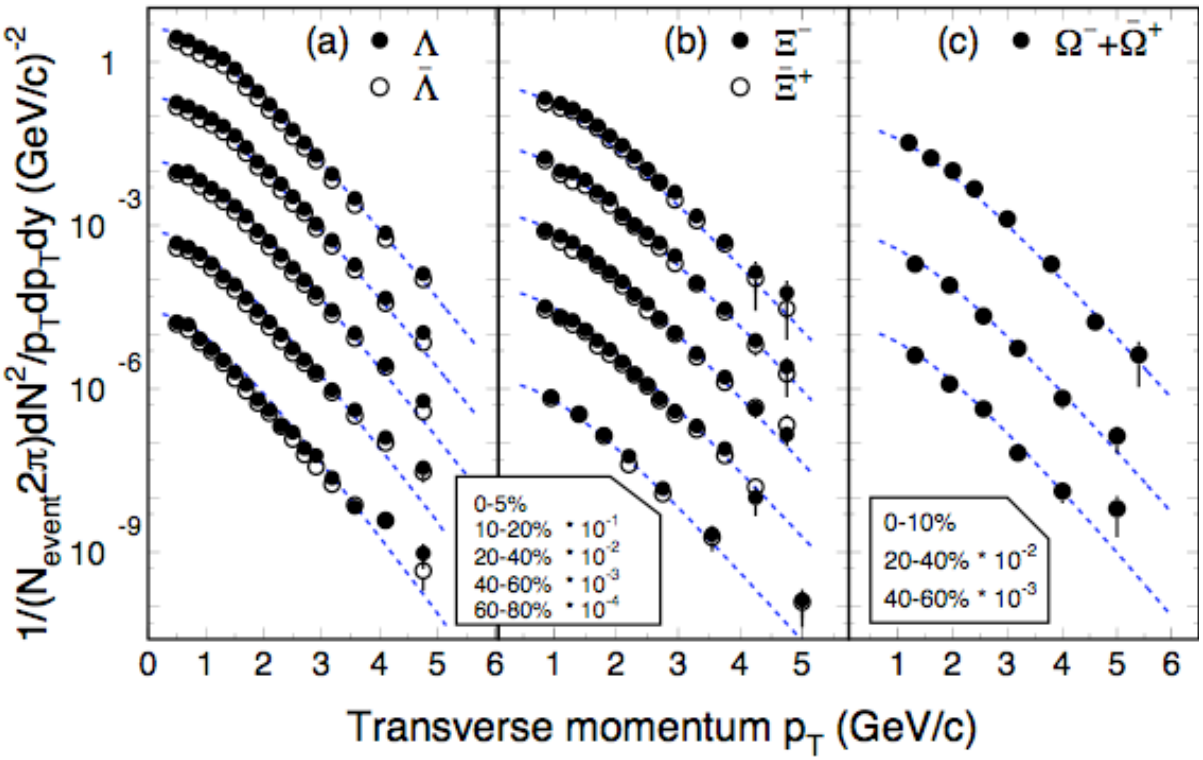
$$m_T = \sqrt{p_T^2 + m^2}$$

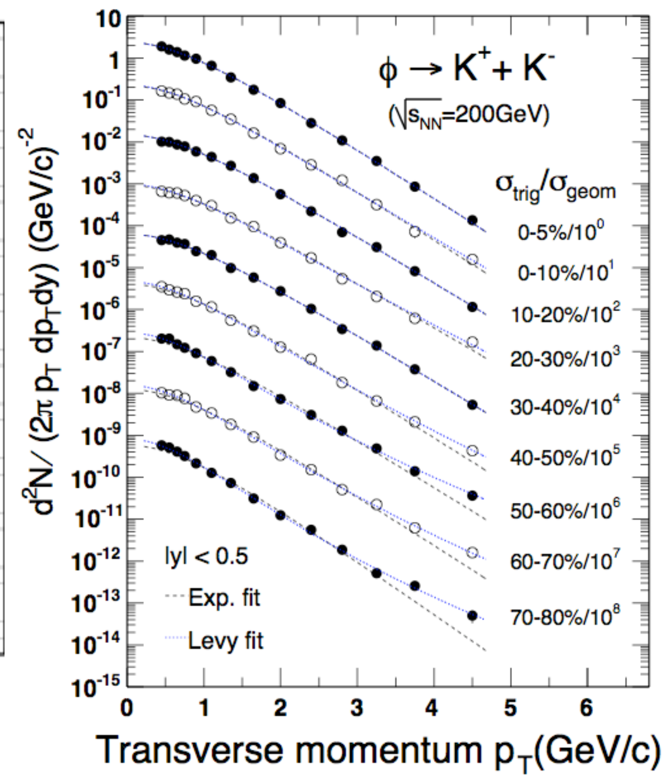
Multi-strange hadron spectra are exponential in their shapes.

STAR white papers - Nucl. Phys. A757, 102(2005).

STAR: Strange Hadrons

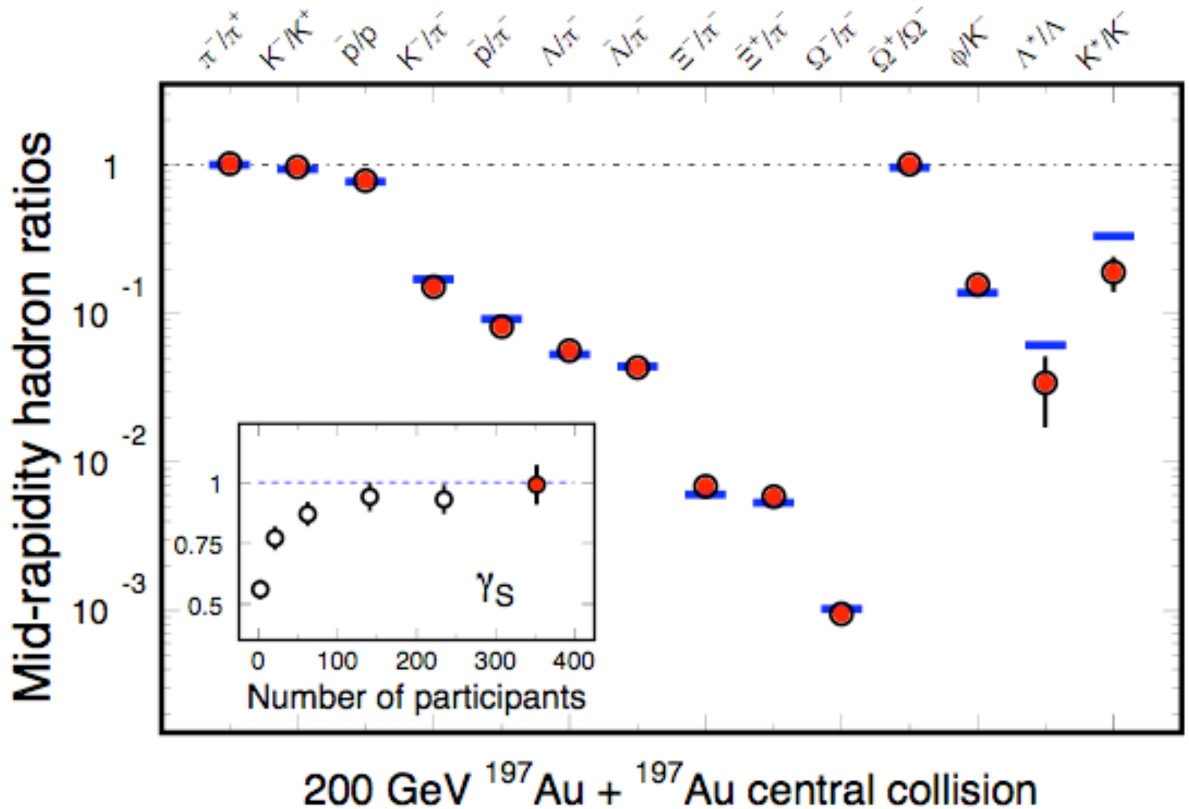
200 GeV Au + Au Collisions





STAR: *J. Adams et al., PRL, **98**, 060301(07)* *PRL in print, 2007.*

Yields Ratio Results



data

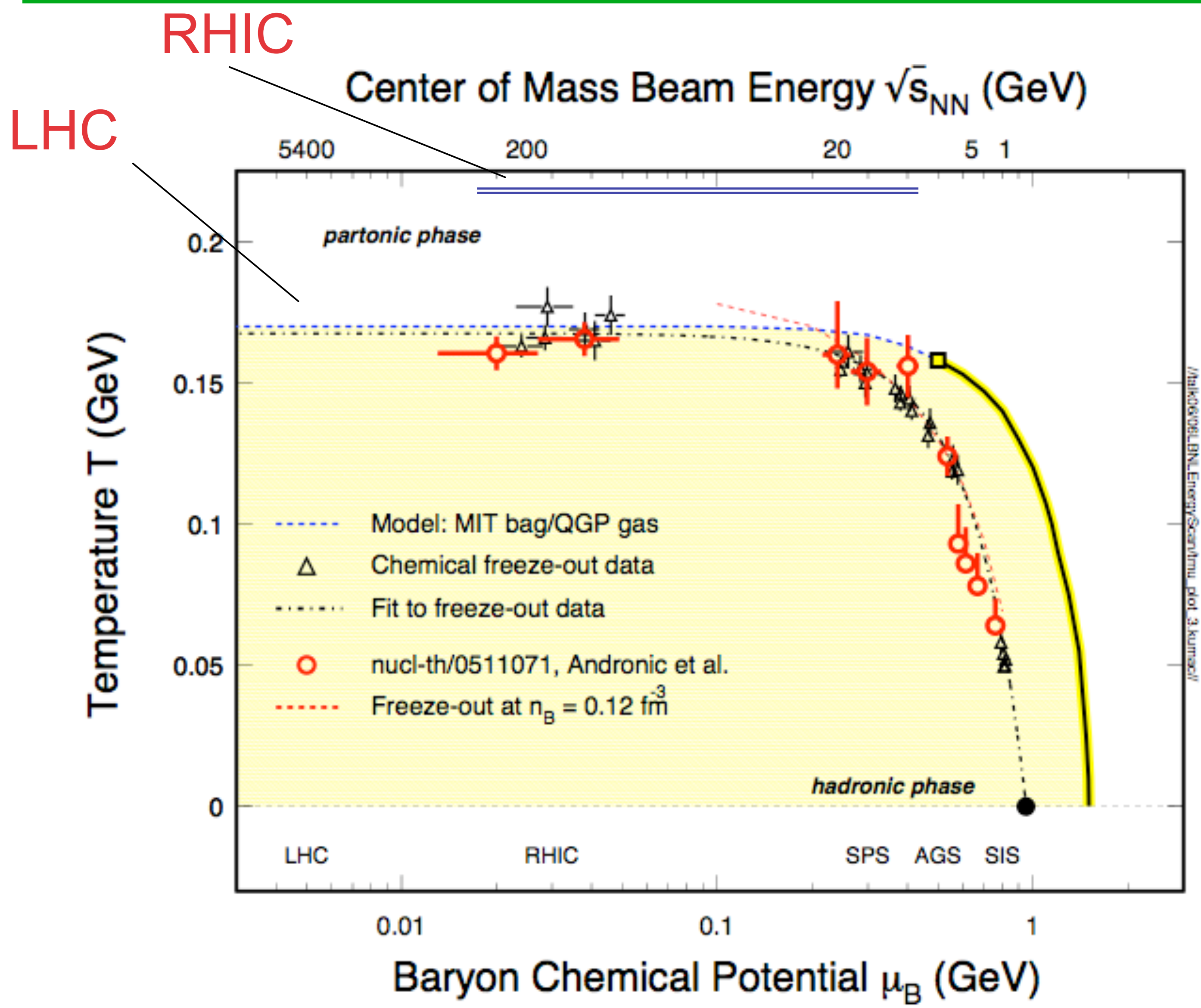
Thermal model fits

T_{ch} = 163 ± 4 MeV

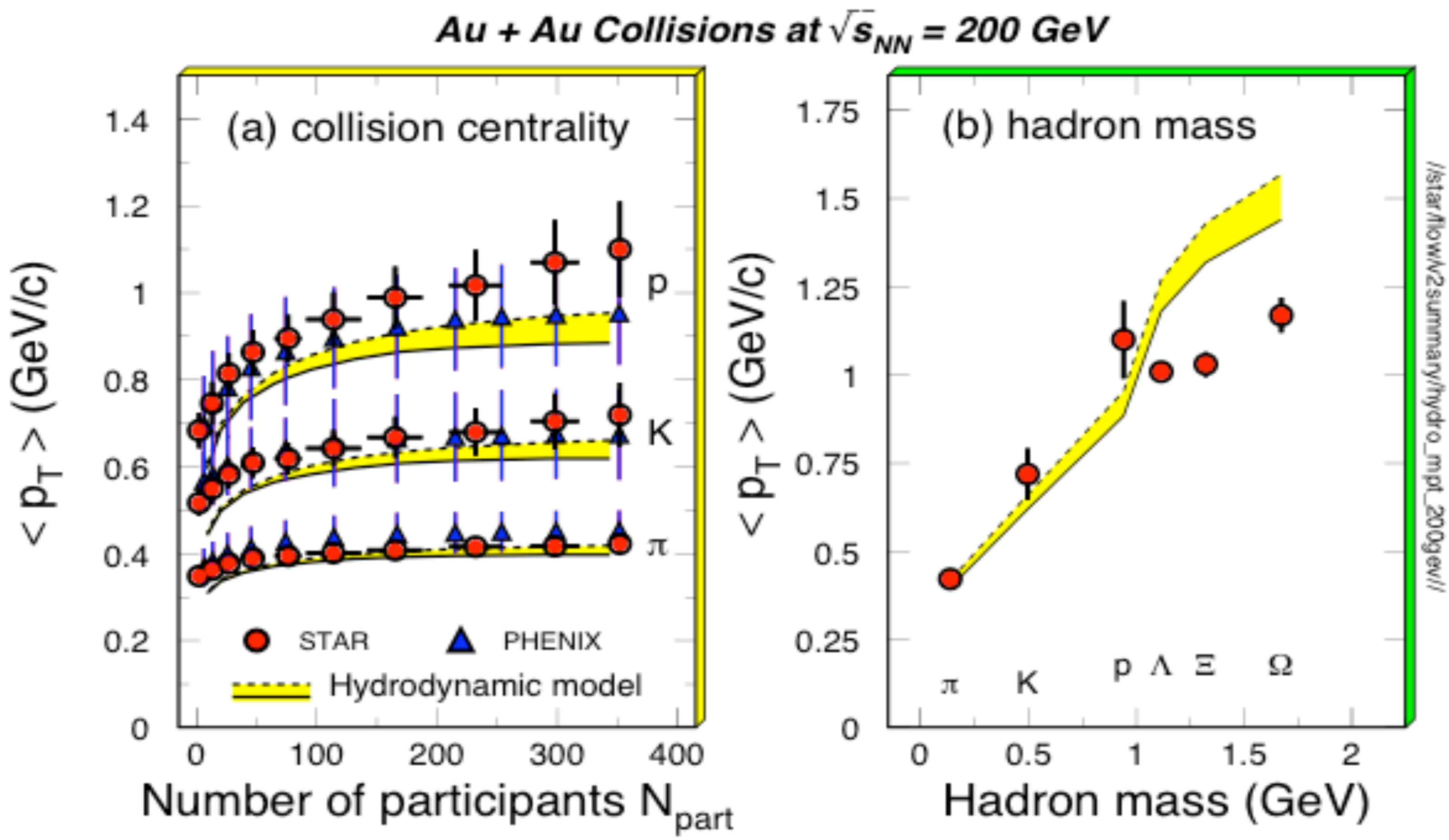
μ_B = 24 ± 4 MeV

- In central collisions, thermal model fit well with γ_S = 1. **The system is thermalized at RHIC.**
- Short-lived resonances show deviations. **There is life after chemical freeze-out.** RHIC white papers - 2005, Nucl. Phys. *A757*, STAR: p102; PHENIX: p184.

QCD Phase Diagram



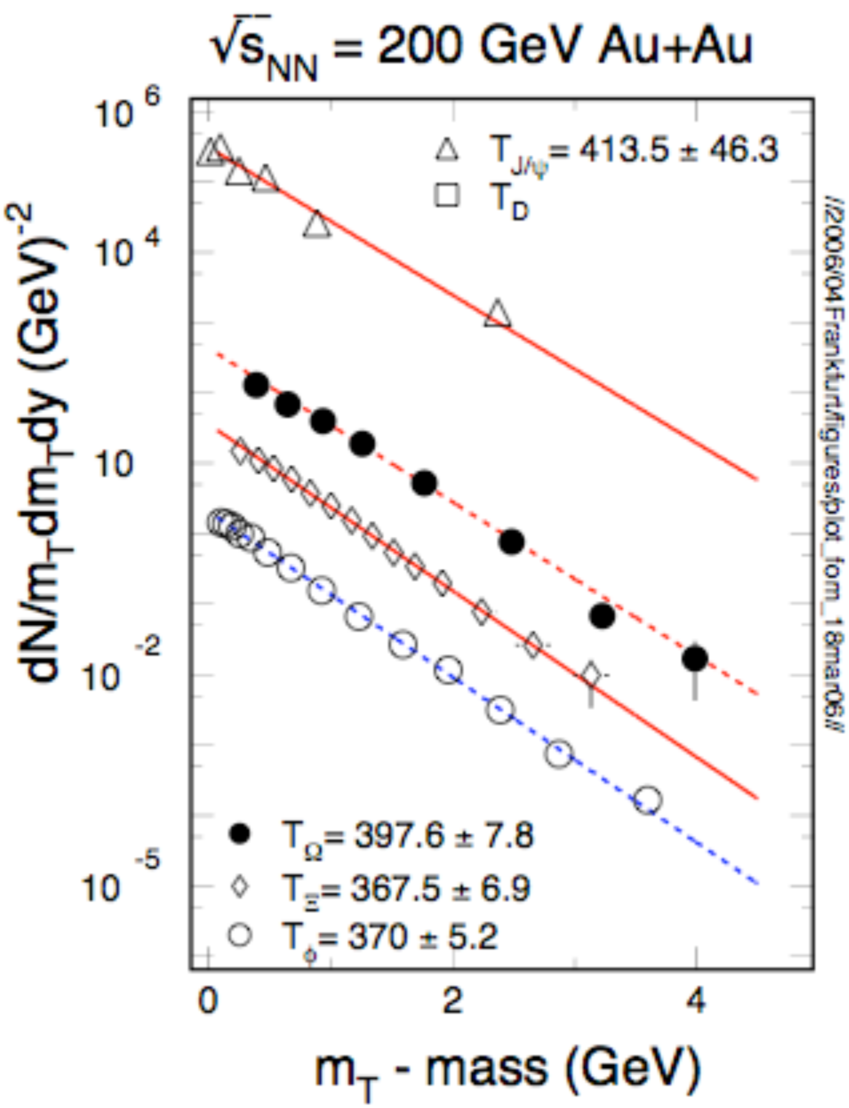
Compare with Hydrodynamic Model



- Hydrodynamic model fit to pion, Kaon, and proton spectra;
- Over predicted the values of $<p_T>$ for multi-strange hadrons who are '***early*** freeze-out'

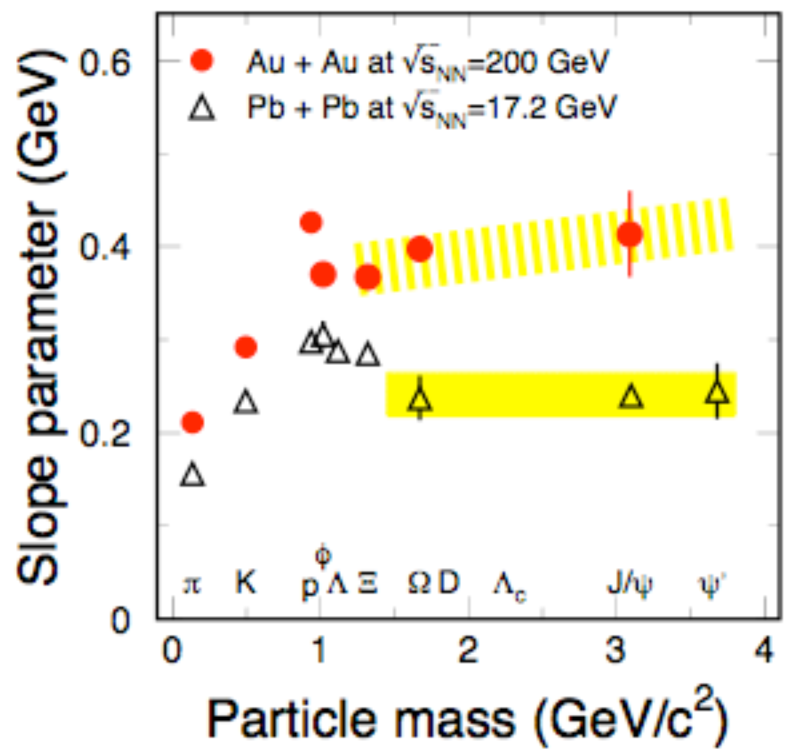
P. Kolab and R.Rapp, PRC

Slope Parameter Systematics



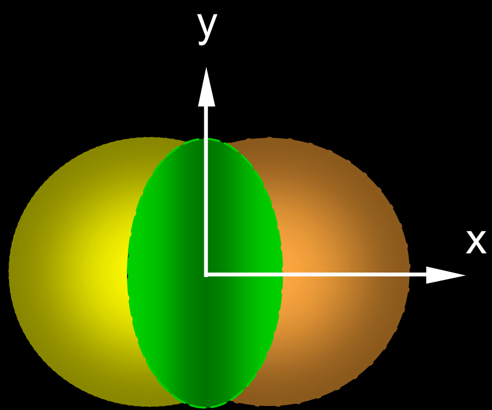
$$m_T = \sqrt{p_T^2 + m^2}$$

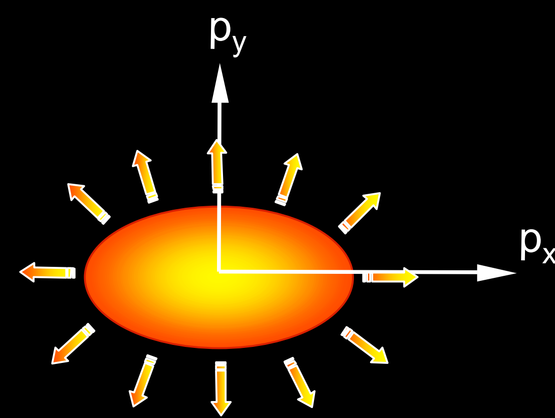
$$f \propto exp(-m_T/T_{slope})$$



Anisotropy Parameter v_2

coordinate-space-anisotropy ⇨ momentum-space-anisotropy

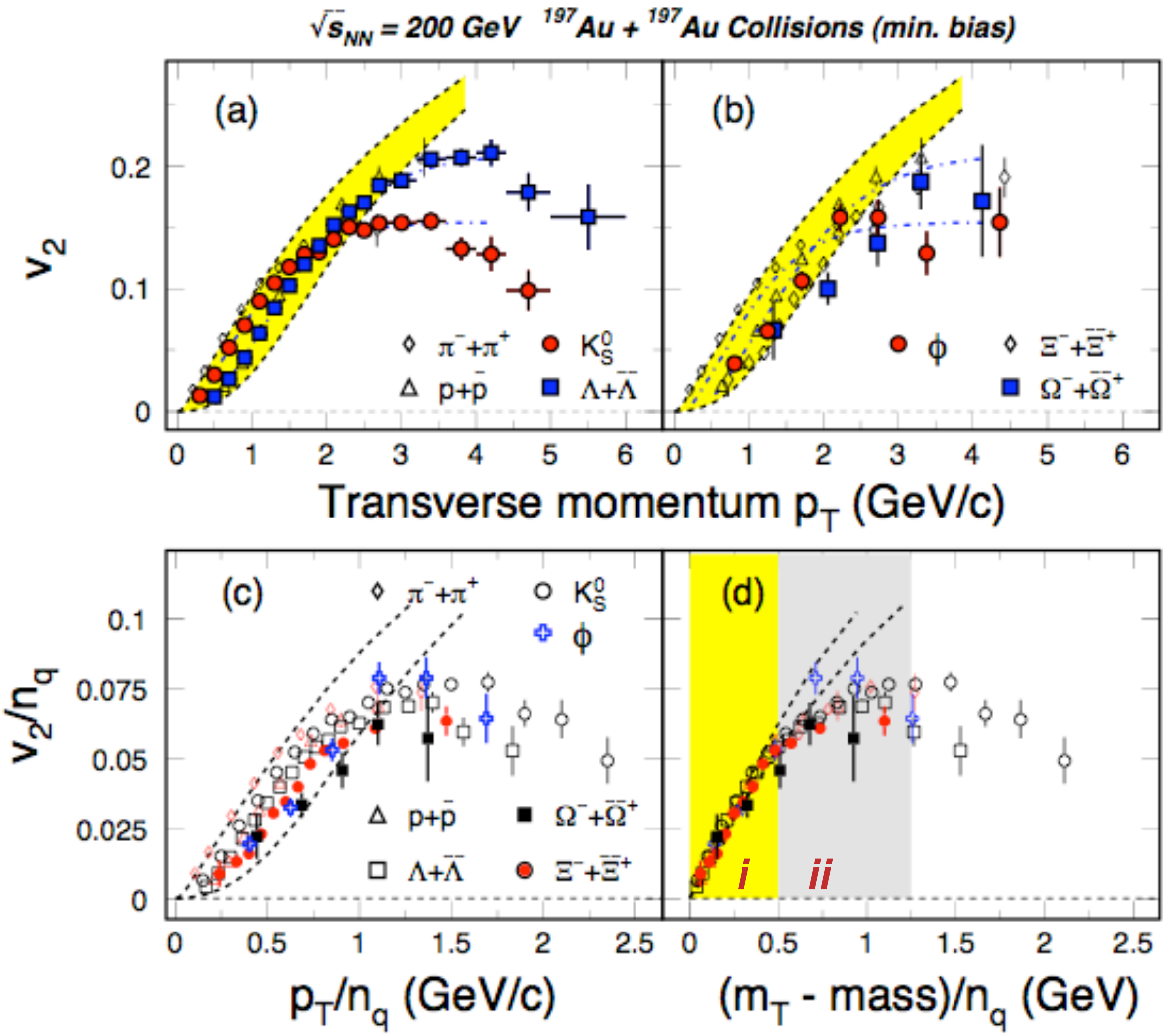




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

Collectivity, Deconfinement at RHIC



- v_2 of light hadrons and multi-strange hadrons
- scaling by the number of quarks

At RHIC:

➪ **m_T - NQ scaling**

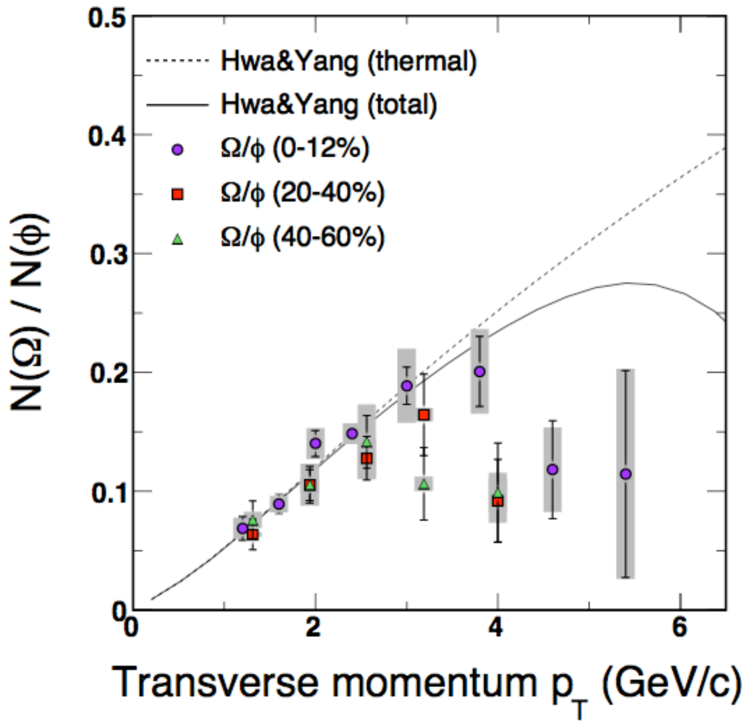
➪ **Partonic Collectivity**

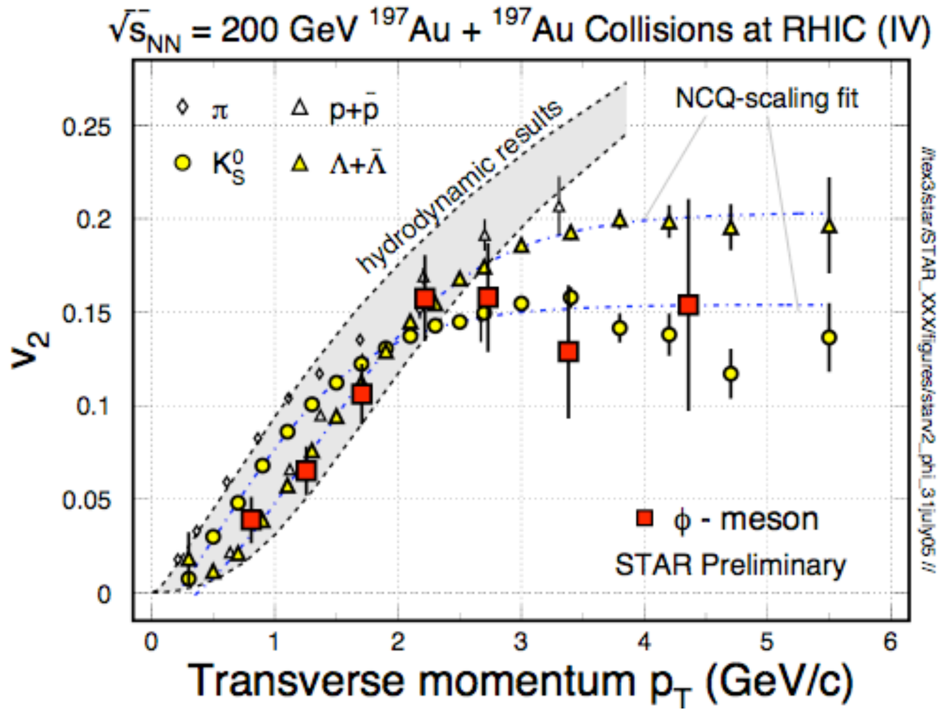
➪ **Deconfinement**

*PHENIX: PRL**91**, 182301(03)*
*STAR: PRL**92**, 052302(04), **95**, 122301(05)*
nucl-ex/0405022, QM05

S. Voloshin, NPA715, 379(03)
*Models: Greco et al, PR**C68**, 034904(03)*
Chen, Ko, nucl-th/0602025
*Nonaka et al. **PLB583**, 73(04)*
*X. Dong, et al., Phys. Lett. **B597**, 328(04).*
….

ϕ -meson Flow: Partonic Flow





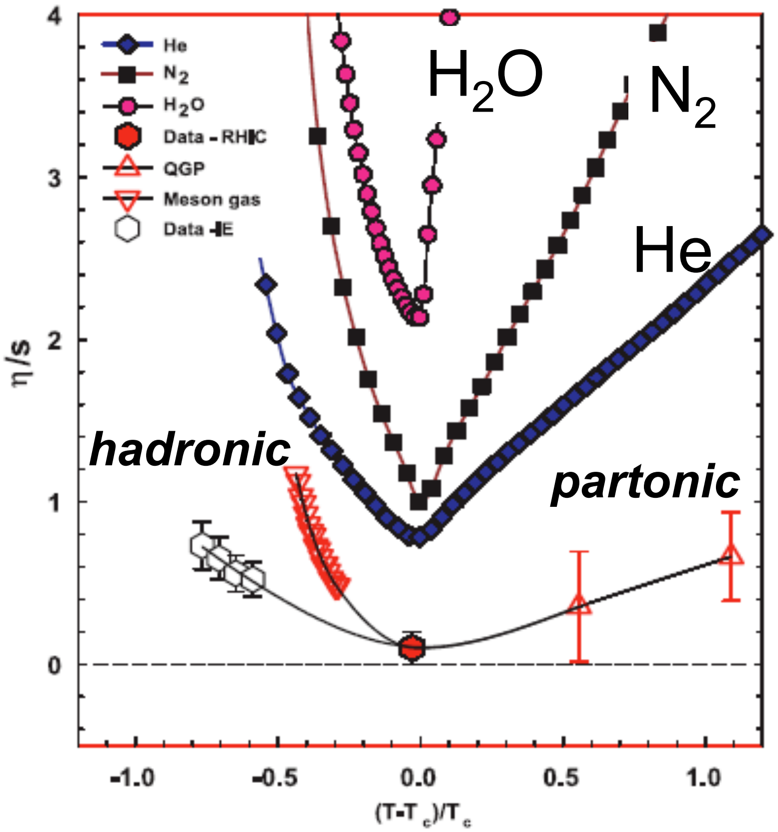
ϕ-mesons are special:

- they are formed via coalescence with thermalized s-quarks
- they show strong collective flow

'They are made via coalescence of seemingly thermalized quarks in central Au+Au collisions, the observations imply *hot and dense matter with partonic collectivity* has been formed at RHIC'

STAR: Phys. Rev. Lett., In print nucl-ex/0703033; Phys. Lett. B612, 81(2005)

Viscosity and the Perfect Fluid



Caption: The viscosity to entropy ratio versus a reduced temperature.

Lacey et al. PRL **98**:092301(07)
hep-lat/0406009
hep-ph/0604138

The universal tendency of flow to be dissipated due to the fluid's ***internal friction*** results from a quantity known as the **shear viscosity**. All fluids have non-zero viscosity. The larger the viscosity, the more rapidly small disturbances are damped away.

Quantum limit: $\eta/s_{AdS/CFT} \sim 1/4\pi$

pQCD limit: ~ 1

At RHIC: ideal (η/s = 0) hydrodynamic model calculations fit to data ⇒

Perfect Fluid at RHIC?!

Lesson learned II: EoS Results

In Au + Au collisions at RHIC:

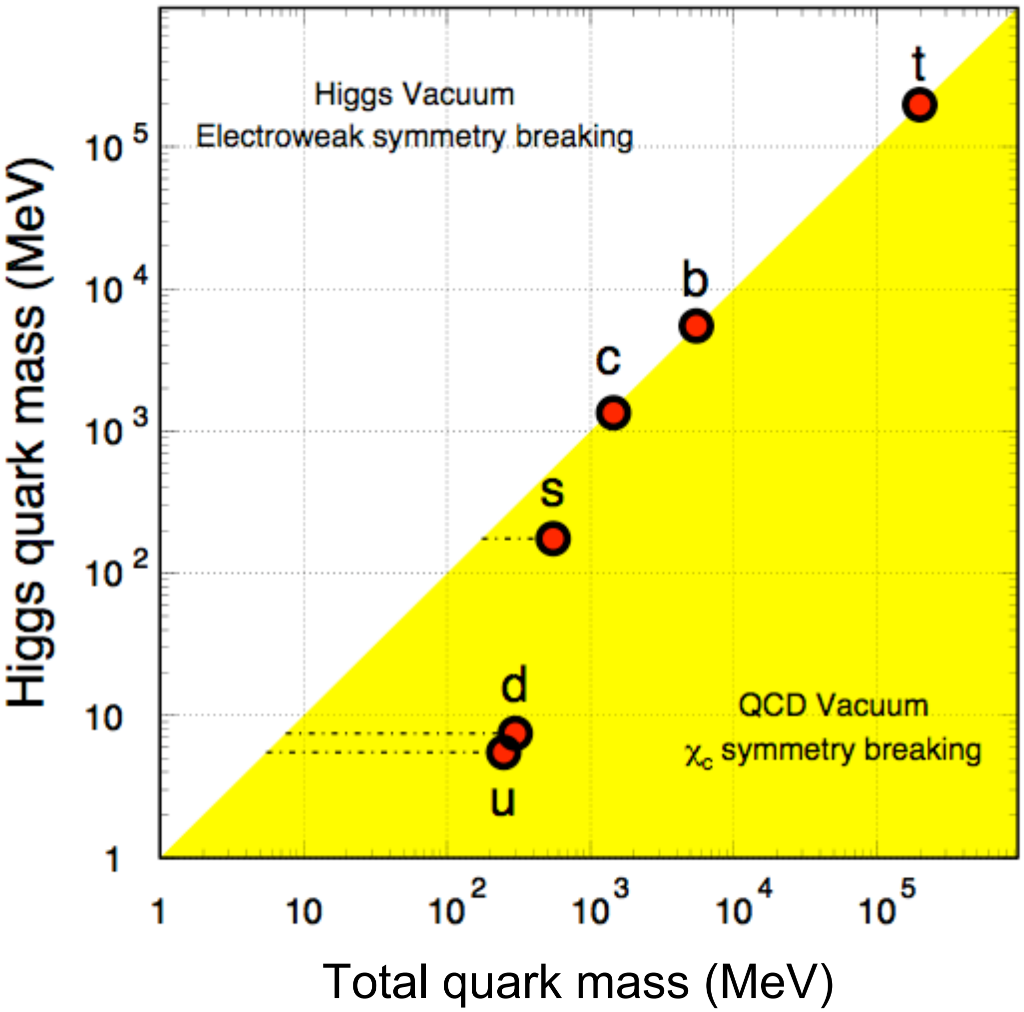
(1) Hadron yields in the state of equilibrium - chemical freeze-out near the transition temperature

(2) The yields $N(\Omega)/N(\phi)$ ratios indicate thermalization

(3) **Partonic Collectivity** and de-confinement

⇨ ***Test light quark thermalization with heavy flavor probes***

Quark Masses



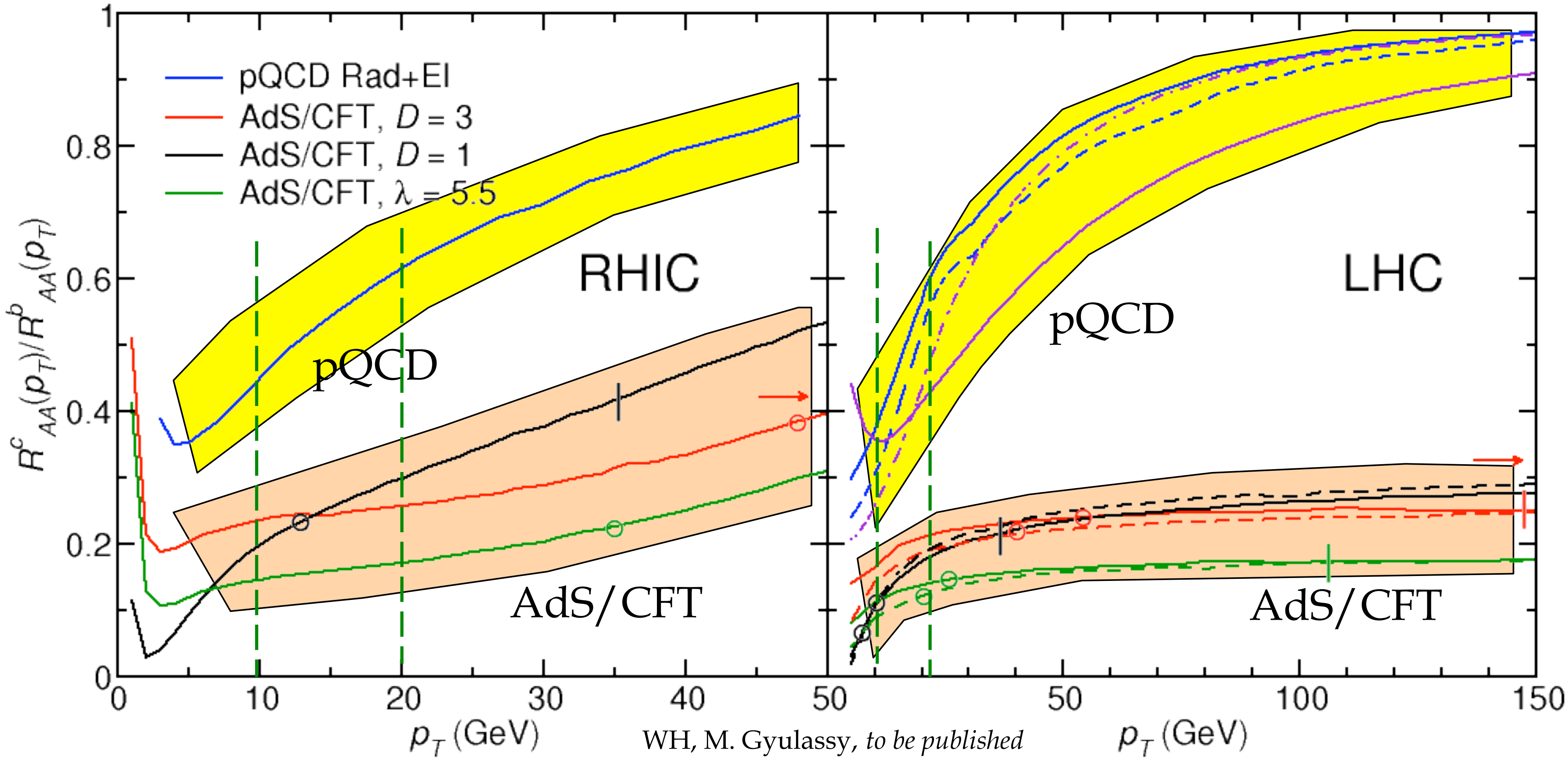
- Higgs mass: electro-weak symmetry breaking. (current quark mass)
- QCD mass: Chiral symmetry breaking. (constituent quark mass)

⇨ Strong interactions do not affect heavy-quark masses.

⇨ Important tool for studying properties of the hot/dense medium at RHIC.

⇨ Test pQCD predictions at RHIC, including the effect of color factors.

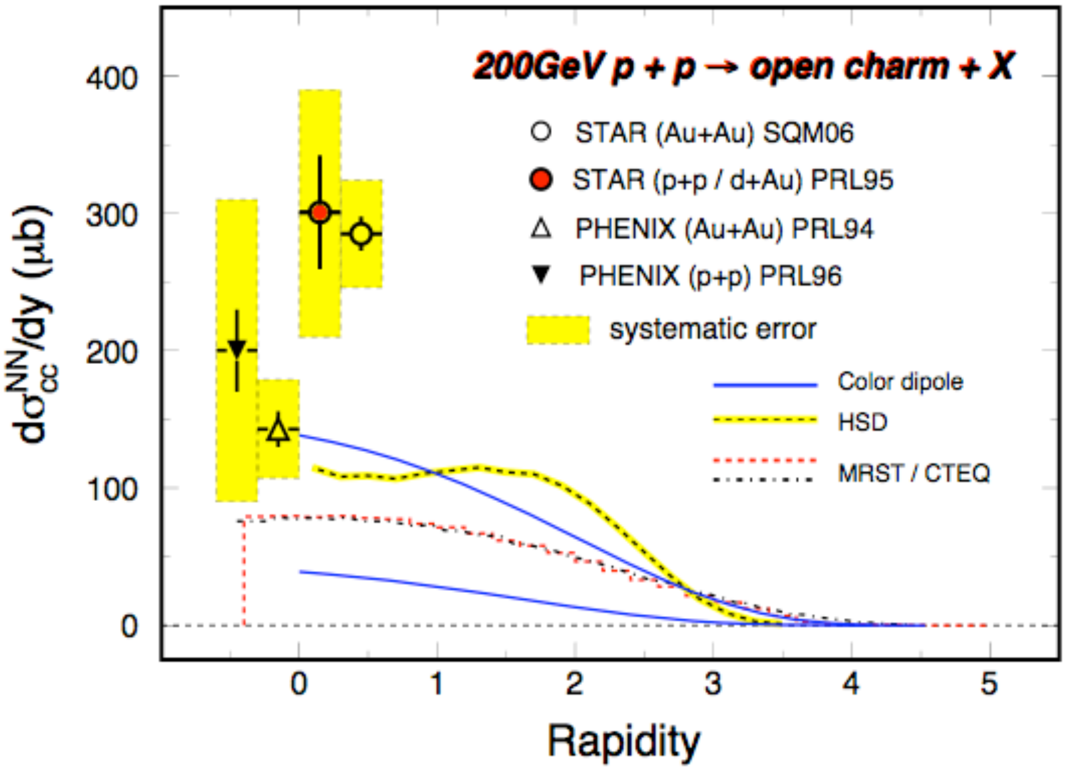
The R^{cb} Ratio: pQCD vs. AdS/CFT

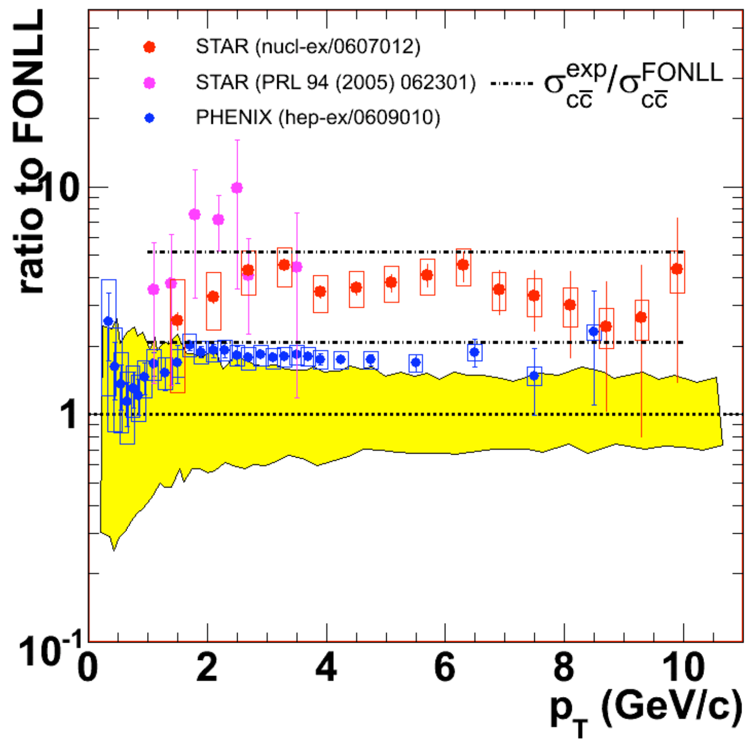


1) Ratio of Charm over Bottom ⇒ separate the energy loss mechanism and the limit on η(T)/s(T)
2) At RHIC, AdS/CFT more valid at higher p_T due to $T_{RHIC} < T_{LHC}$

W. Horowitz and M. Gyulassy, nucl-th/07062336

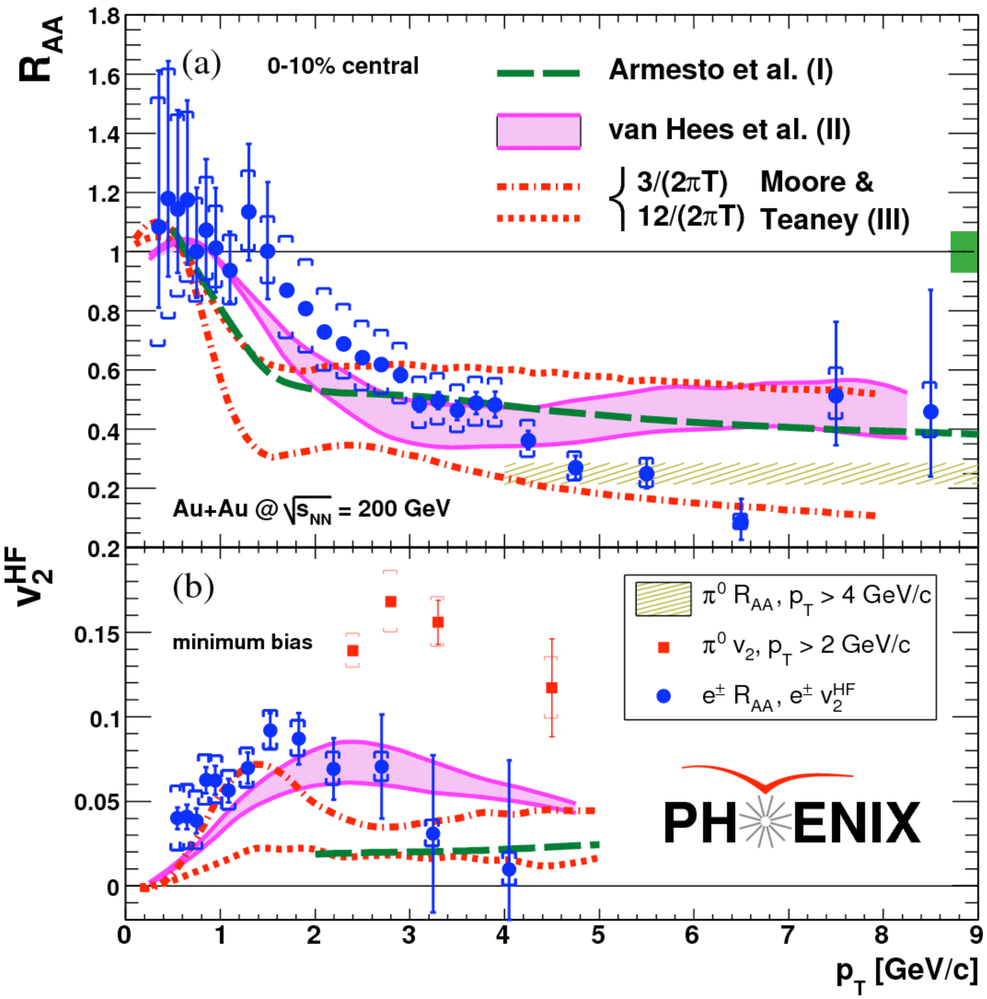
Charm Cross Sections at RHIC





1) Large systematic uncertainties in the measurements
2) Theory under predict by a factor ~ 2 and
STAR ~ 2 x PHENIX
3) Directly reconstructed charm hadrons ⇒Upgrades

HQ Decay Electron Data



Phenix: *PRL* ***98*** *172301(07)*

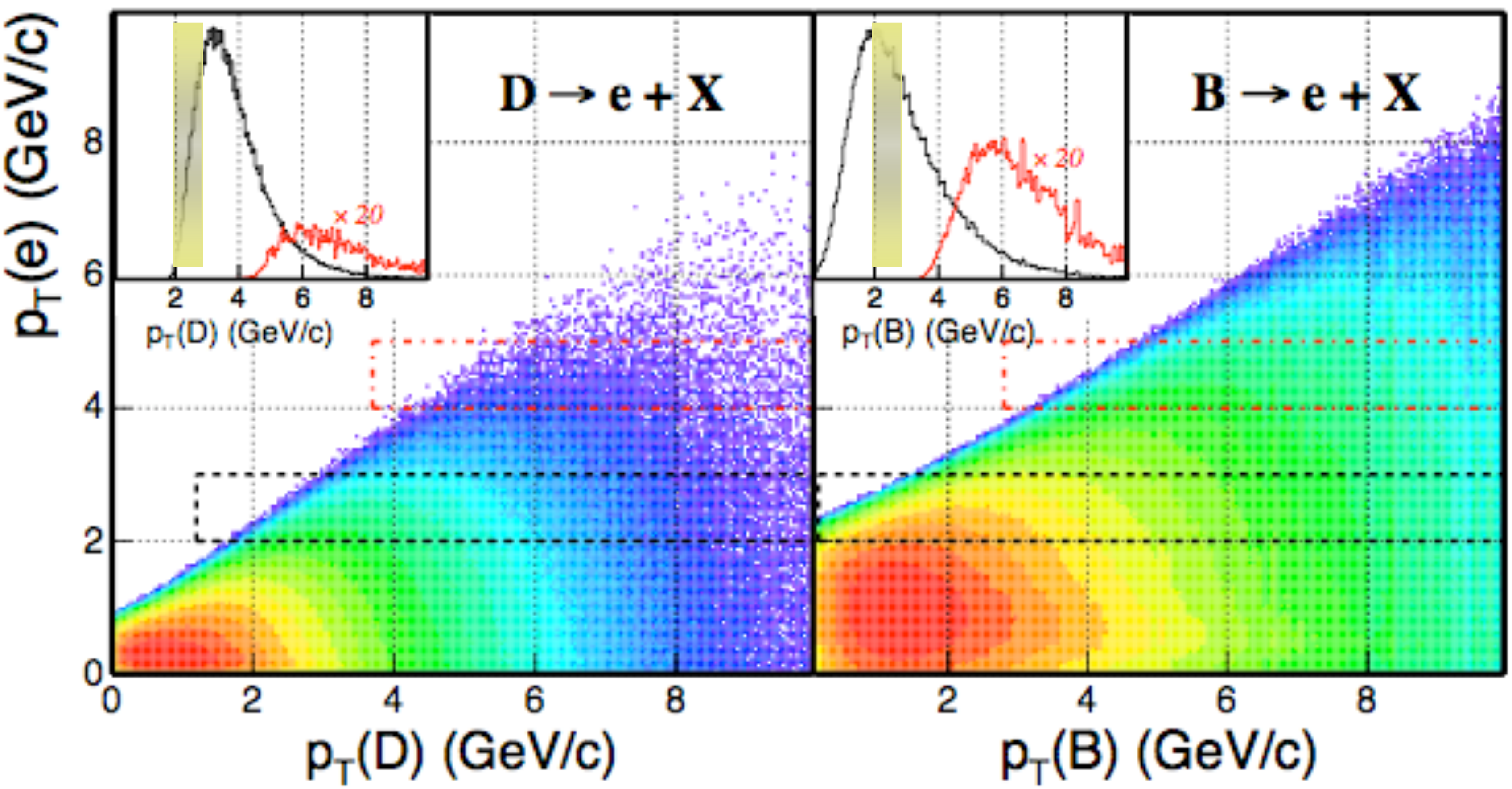
- Large p_T: suppression as light quark hadrons;
- Low p_T: non-vanishing v_2

⇒ Possible coupling of the heavy quarks with the hot/dense medium at RHIC.

Unknown: p_T dependence of the bottom quark contributions

Unknown: collectivities of light- and heavy-quarks

Decayed Electron p_T vs. b- and c-hadron p_T



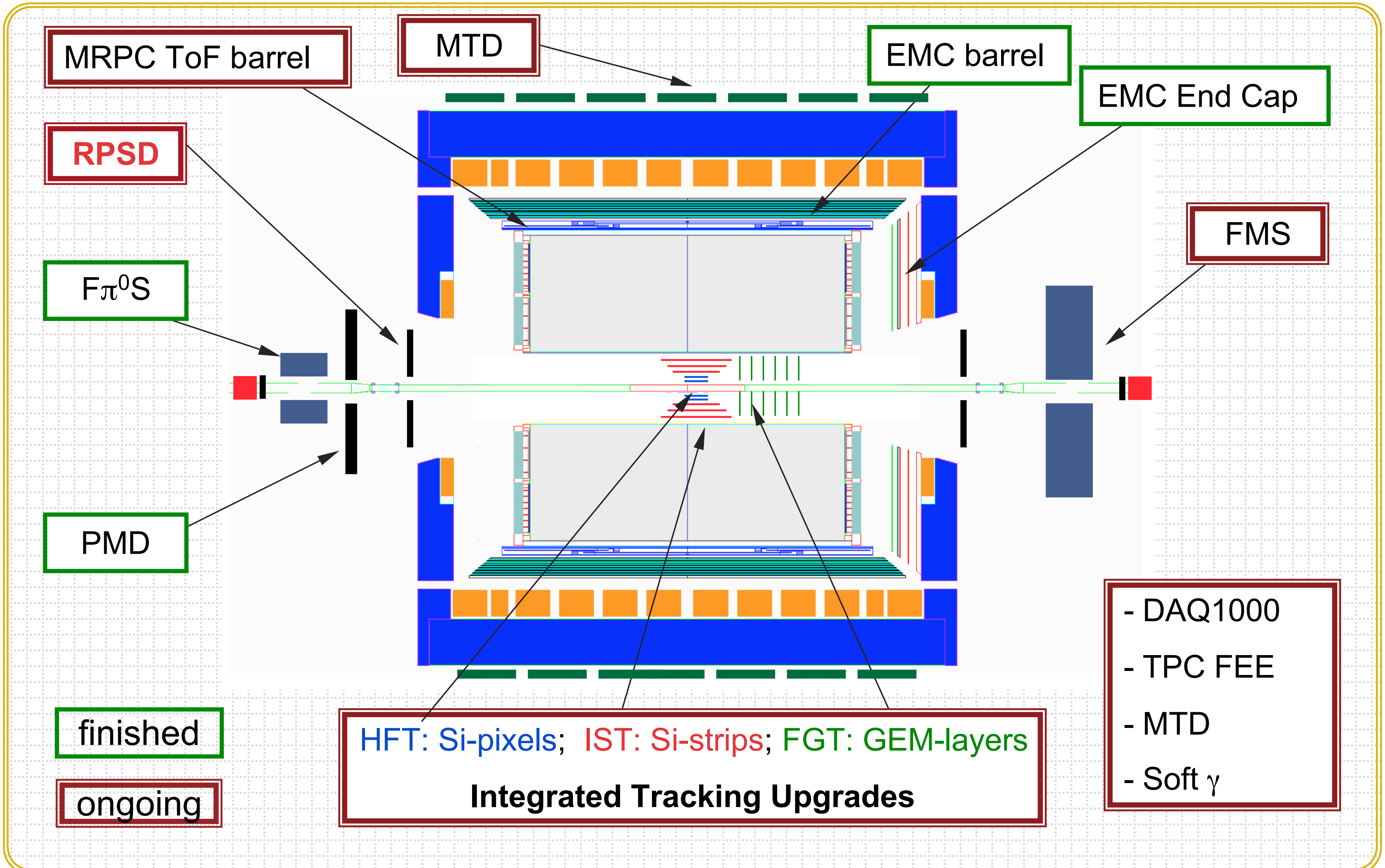
The correlation between the decayed electrons and heavy-flavor hadrons is weak.

Pythia calculation   Xin Dong, USTC October 2005

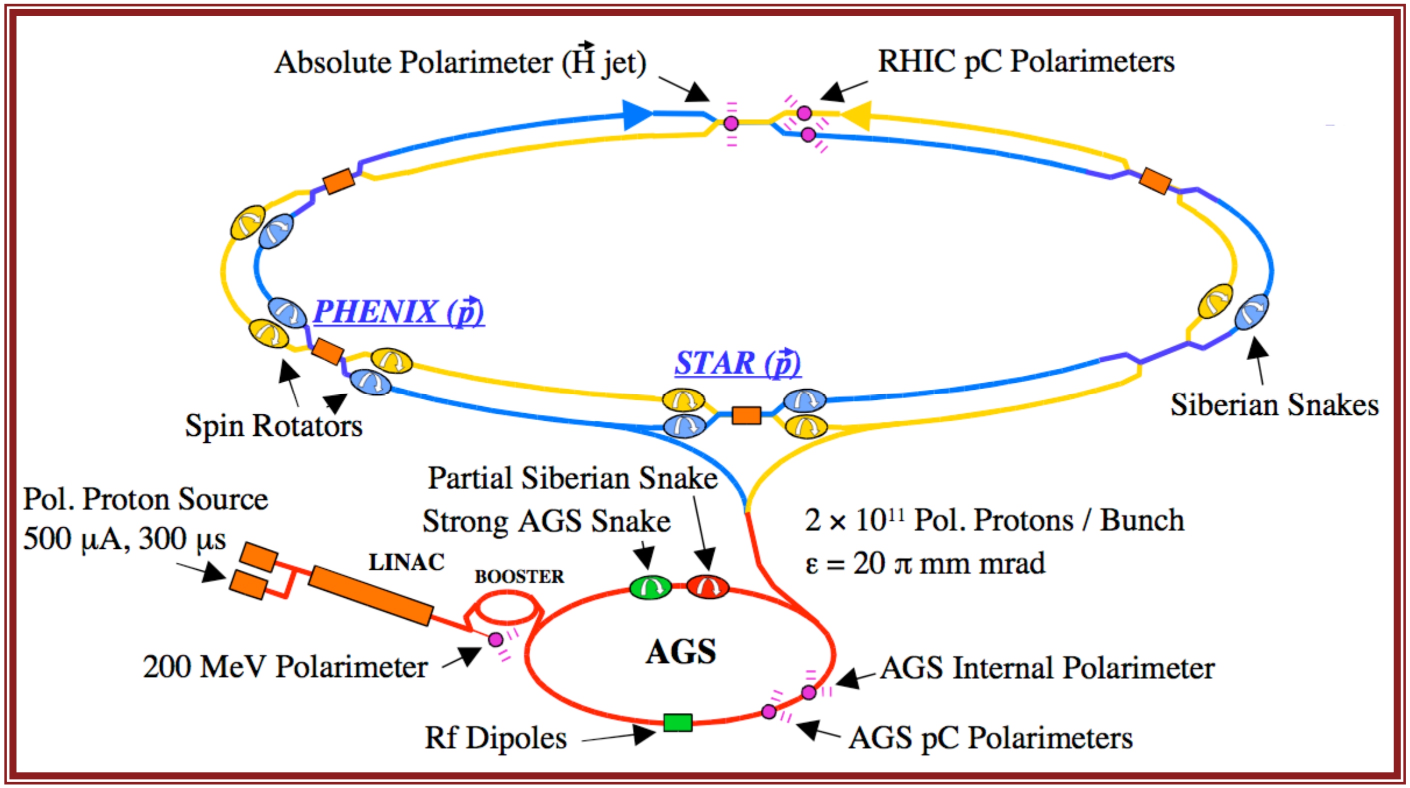
Upgrades Are Needed!

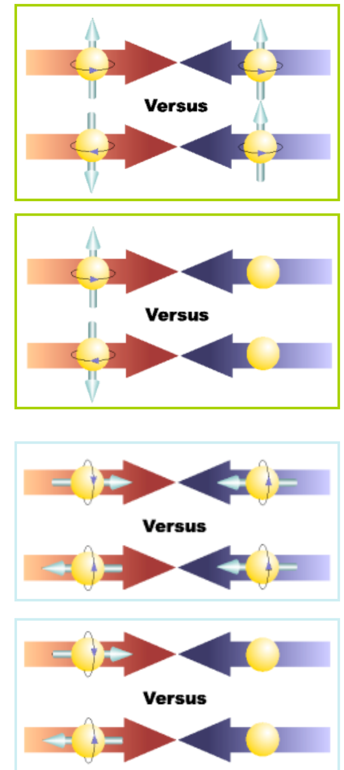
When systematic error dominates the data, new experiments (detectors) are called for.

STAR Upgrades



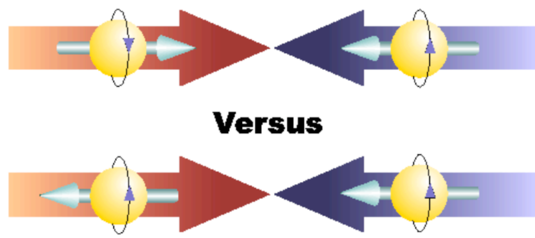
RHIC Spin Physics Program





New measurements: proton-proton collisions with longitudinal and transverse polarizations at $\sqrt{s}$ = 200 - 500 GeV will allow us to study the origin of proton spin.

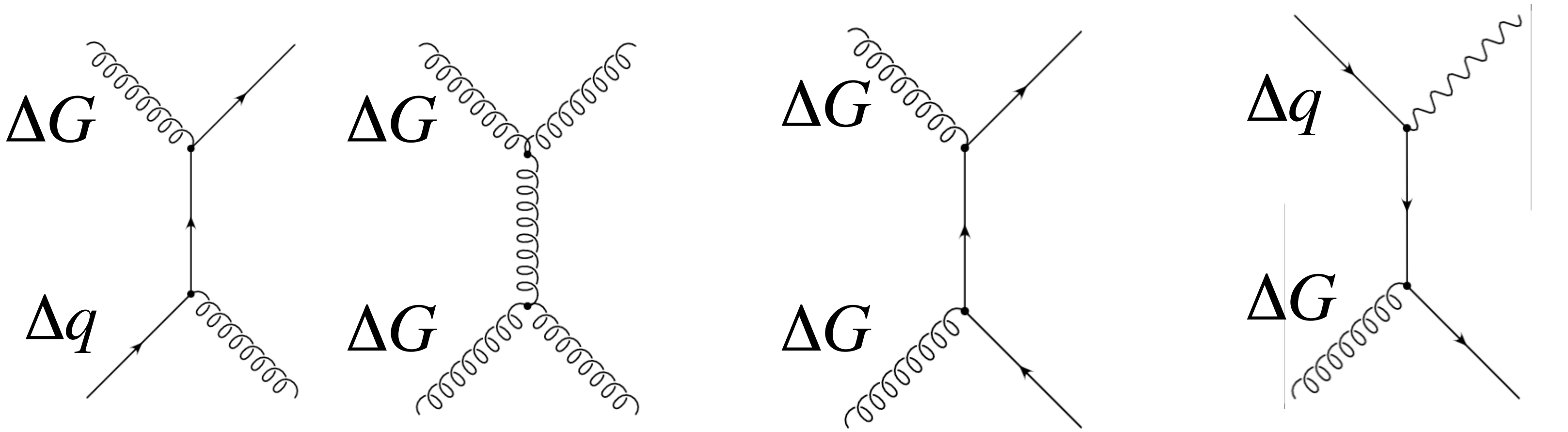
Longitudinal Spin Measurements



$$A_{LL} = \frac{(\sigma_{++} + \sigma_{--}) - (\sigma_{+-} + \sigma_{-+})}{(\sigma_{++} + \sigma_{--}) + (\sigma_{+-} + \sigma_{-+})}$$

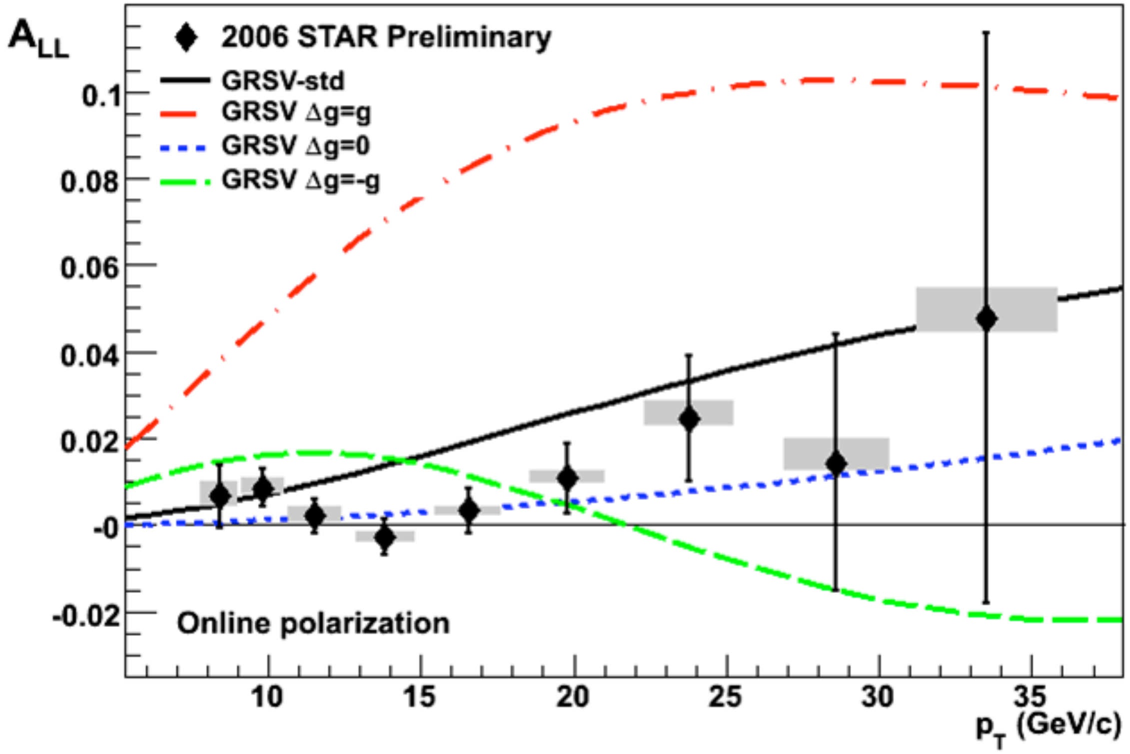
$$= \frac{1}{P_1 P_2} \frac{N_{++} - R N_{+-}}{N_{++} + R N_{+-}}$$

$$\vec{p} + \vec{p} \rightarrow jet(s) + X \qquad \vec{p} + \vec{p} \rightarrow c\bar{c}, b\bar{b} + X \qquad \vec{p} + \vec{p} \rightarrow \gamma + jet$$



RHIC: *P = 0.4-0.7; I = 300-800 pb^{-1}; √s = 200-500 GeV*

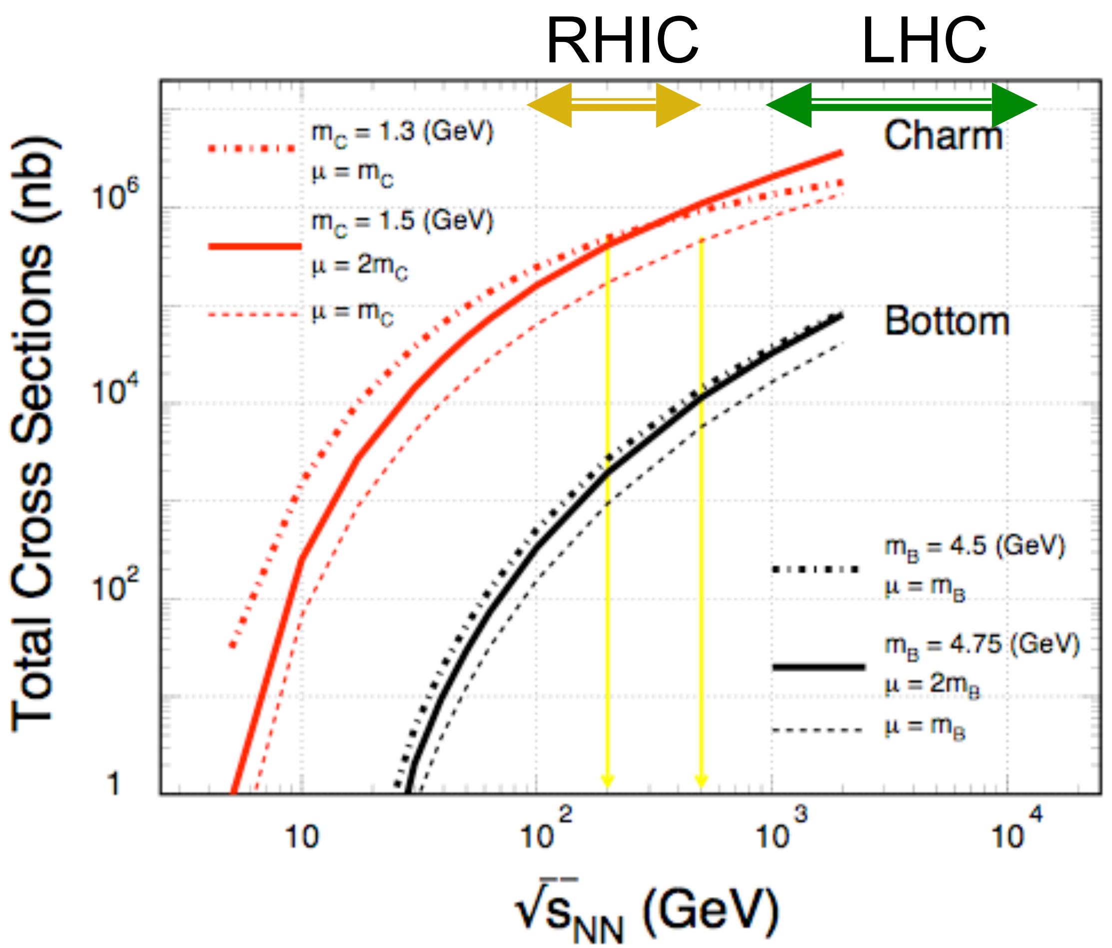
Recent Spin Results



Summary: "… disfavor at 98% C.L. maximal positive gluon polarization in the polarized nucleon."

STAR: "Longitudinal double-spin asymmetry …" arXiv: 0710.2048, sub. to PRL
*(i) Phys. Rev. Lett. **99** (2007) 142003; (ii) Phys. Rev. Lett. **97** (2006) 252001*
*(iii) Phys. Rev. Lett. **92** (2004) 171801*

Heavy Quark Production



The NLO pQCD predictions of charm and bottom for the total p+p hadro-production cross sections.

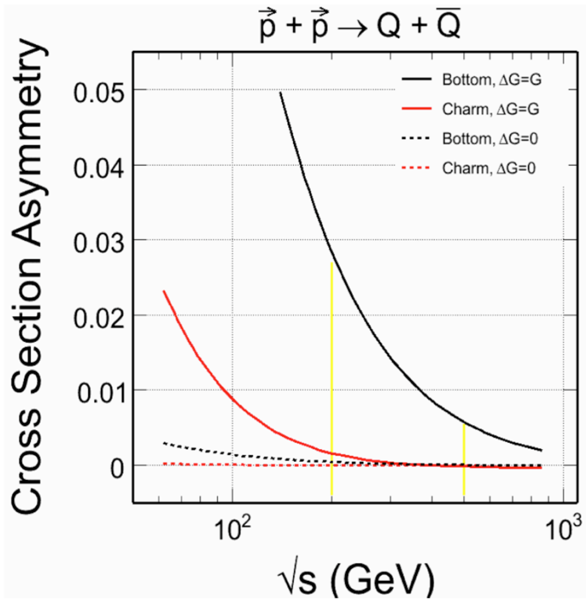
The renormalization scale and factorization scale were chosen to be equal.

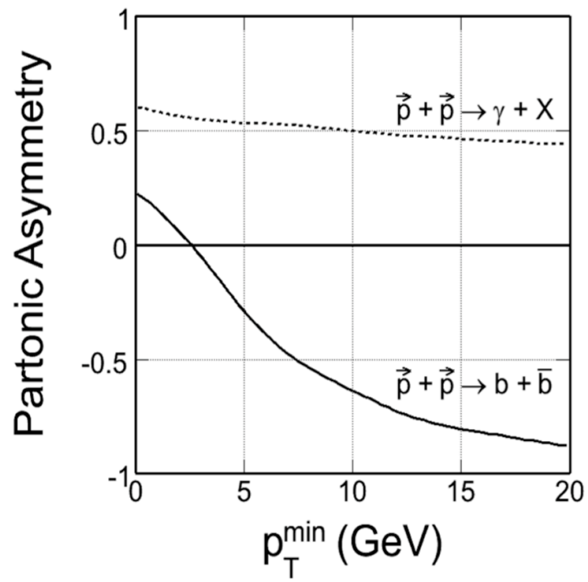
RHIC: 200, 500 GeV
LHC: 900, 14000 GeV

Ideal energy range for studying pQCD predictions for heavy quark productions.

Necessary references for both heavy ion and spin programs at RHIC.

Physics Program - HFT





- Heavy quark production: Complimentary probe for gluon polarization and open the study of spin dynamics to quark mass.

- Partonic asymmetry on event kinematics - Never tested before!

- NU: needs references

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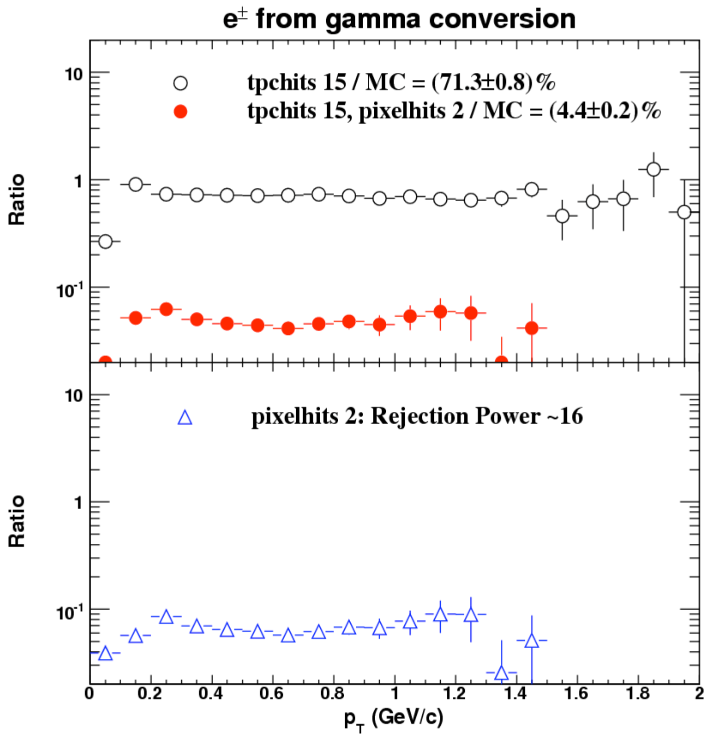
1) Au+Au collisions

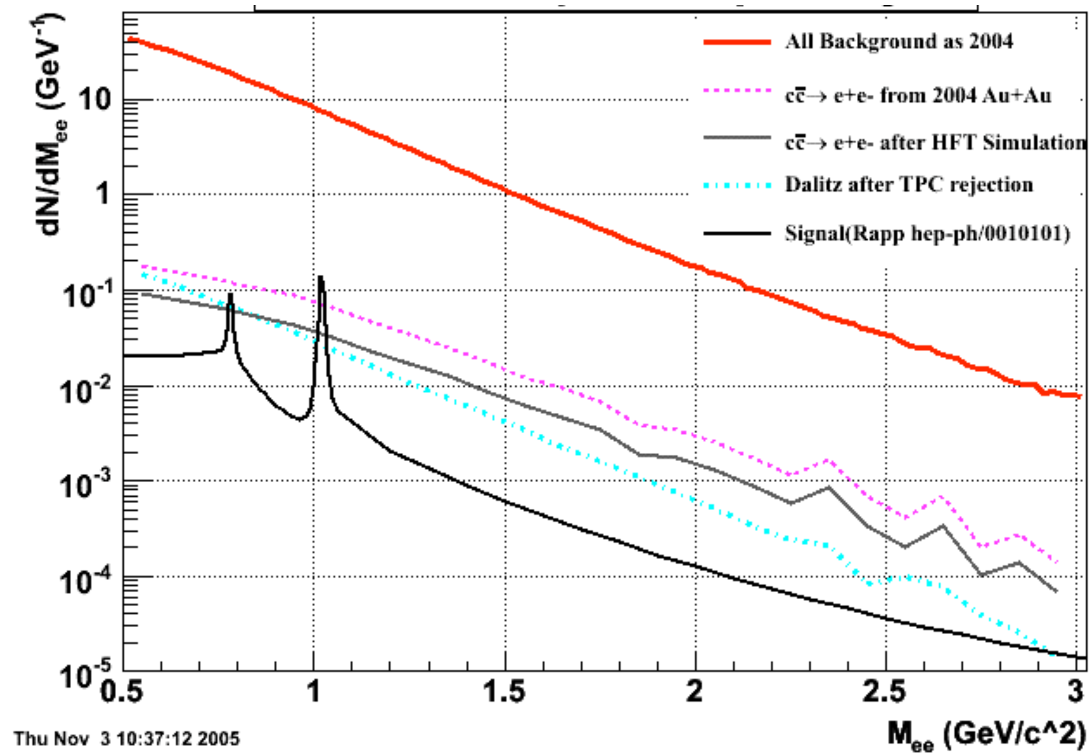
- measure heavy-quark hadron v_2, the heavy-quark collectivity to study light-quark thermalization
- measure di-leptions to study the direction radiation from the hot/dens medium
- measure heavy-quark energy loss to study pQCD in hot/dense medium

2) p+p collisions

- measure energy dependence of the heavy-quark production
- measure CP with W production at 500 GeV
- measure gluon structure with heavy quarks and direct photons

Conversion Rejections with HFT

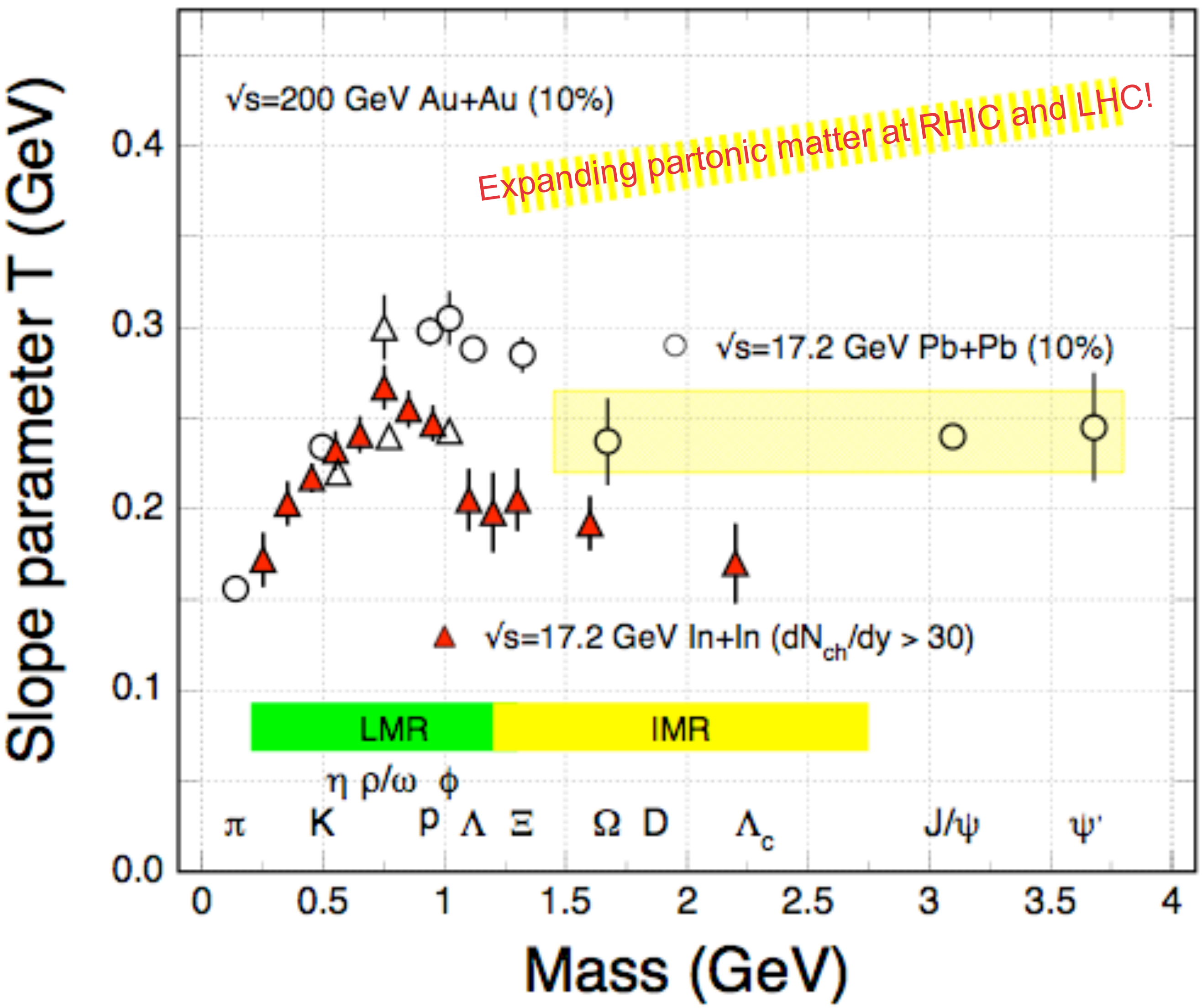




- **Background: $\gamma \rightarrow e^+e^-$**
- **HFT discriminates background**
- **Statistics comparable to NA60**
- **Charm background**

Detectors	ω	ϕ
TPC+TOF+HFT	20K	6K

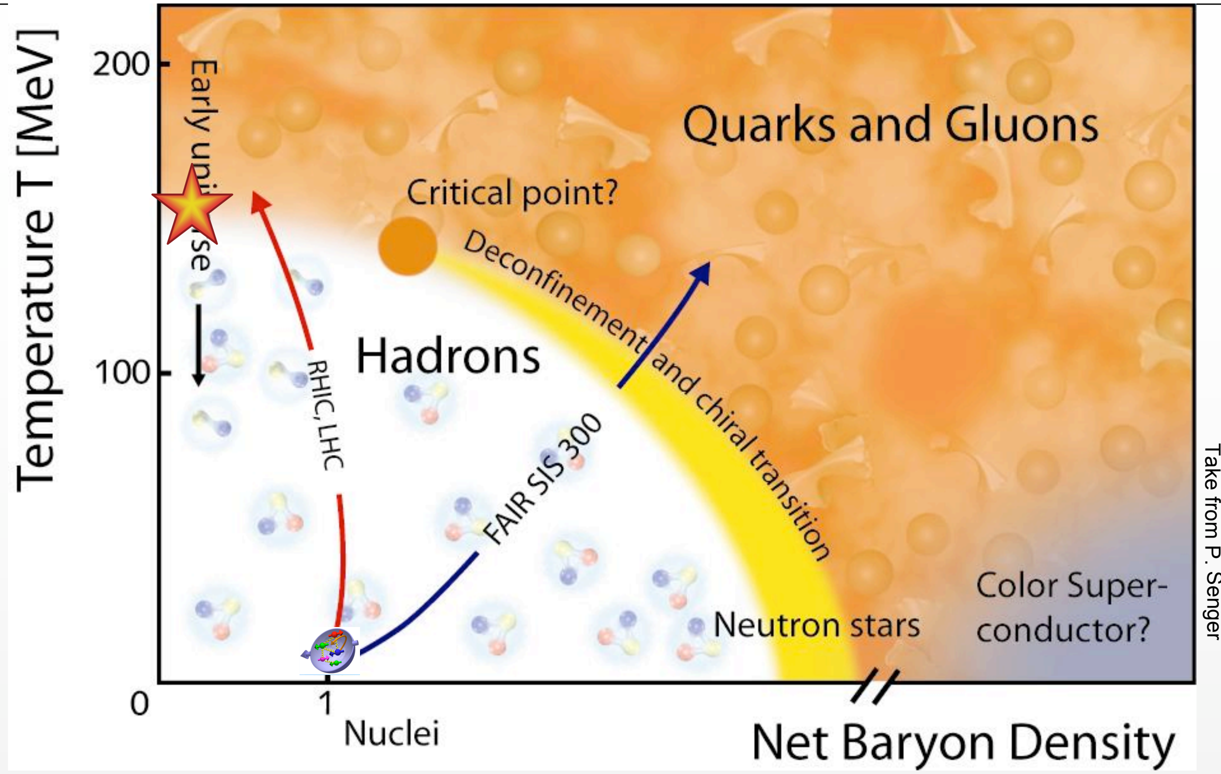
Direct Radiation of Matter



The di-leptons will allow us to measure the direct radiation of matter with partonic degrees of freedom, no hadronization!

Puzzle 1: dramatic change of the slope parameter at $m \sim 1$ GeV

Puzzle 2: source of T at $m \geq 1.5$ GeV



1) Heavy-quark program - Heavy Ion Collisions:
   - Study ***medium properties*** at high-energy nuclear collisions
   - pQCD in hot and dense environment

2) Heavy-quark program - Polarized p+p Collisiosn:
   - Study nucleon heicity structure with QCD

3) RHIC Energy Scan / GSI program:
   - Search for the possible ***phase boundary*** and ***the trial-critical point***.
   - Chiral symmetry restoration